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LITERATURE REVIEW OF REMEDIATION METHODS FOR PCBs IN BUILDINGS

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Disclaimer

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Abstract

Foreword

The U.S. Environmental Protection Agency (EPA) is charged by Congress with protecting the Nation's land, air, and water resources. Under a mandate of national environmental laws, the Agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. To meet this mandate, EPA's research program is providing data and technical support for solving environmental problems today and building a science knowledge base necessary to manage our ecological resources wisely, understand how pollutants affect our health, and prevent or reduce environmental risks in the future.

The National Risk Management Research Laboratory (NRMRL) is the Agency's center for investigation of technological and management approaches for preventing and reducing risks from pollution that threaten human health and the environment. The focus of the Laboratory's research program is on methods and their cost-effectiveness for prevention and control of pollution to air, land, water, and subsurface resources; protection of water quality in public water systems; remediation of contaminated sites, sediments and ground water; prevention and control of indoor air pollution; and restoration of ecosystems. NRMRL collaborates with both public and private sector partners to foster technologies that reduce the cost of compliance and to anticipate emerging problems. NRMRL's research provides solutions to environmental problems by: developing and promoting technologies that protect and improve the environment; advancing scientific and engineering information to support regulatory and policy decisions; and providing the technical support and information transfer to ensure implementation of environmental regulations and strategies at the national, state, and community levels.

This publication has been produced in support of EPA's mission to protect human health and the environment. It is published and made available by EPA's Office of Research and Development to assist the user community and to link researchers with their clients.

Cynthia Sonich-Mullin, Director
National Risk Management Research Laboratory

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LISt of aPPendIceS

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LISt of abbreVIatIonS and acronymS	
AcGIH	American conference of Governmental Industrial Hygienists
AIHA	American Industrial Hygiene Association
AMtS	Activated Metal treatment System
ASHRAE	American Society of Heating, Refrigerating and Air conditioning Engineers
AStM	American Society for testing and Materials
AwMA	Air and waste Management Association
BtS	Bimetallic treatment System
cDc	centers for Disease control and Prevention
cFR	code of Federal Regulations
DoD	Department of Defense
EcP	Electrochemical Peroxidation Process
EH&E	Environmental Health & Engineering, Inc.
EPA	U.S. Environmental Protection Agency
HEPA	High Efficiency Particulate Air
HvAc	Heating, ventilation, and Air conditioning
ISES	International Society for Exposure Science
ISEE	International Society for Environmental Epidemiology
ISIAQ	International Society for Indoor Air Quality
ng/µL	nanograms per microliter
ng/kg	nanograms per kilogram
ng/m^3	nanograms per cubic meter
NASA	National Aeronautics & Space Administration
NIoSH	National Institute for occupational Safety and Health
PcB	Polychlorinated Biphenyl
PPE	Personal Protective Equipment
ppm	parts per million
Pvc	Polyvinyl chloride
RcRA	Resource conservation & Recovery Act
SEtAc	Society for Environmental toxicology and chemistry
tScA	toxic Substances control Act
UcF	University of central Florida
UNEP	United Nations Environment Programme
voc	volatile organic compound
ZVM	Zero-valent Magnesium
µg/m^3	micrograms per cubic meter
µg/L	micrograms per liter

1.0 introduction

Polychlorinated biphenyls (PCBs) are a class of persistent organochlorine chemicals that formerly had numerous commercial applications in the United States. Used primarily as an insulator in electrical equipment, PCBs were also a component of construction materials such as caulk, adhesives, and paints. Concentrations of PCBs in building materials frequently exceed levels authorized by U.S. regulations. A wide range of public and commercial buildings have been identified as being at risk of having PCB-containing materials.

In September 2009, the U.S. Environmental Protection Agency (EPA) provided initial guidance to property managers, particularly administrators of schools, on approaches to managing potential exposures to PCBs in building materials (EPA, 2011a). The guidance from EPA complements the requirements in Title 40 Part 761 of the Code of Federal Regulations for characterization and disposal of waste materials that contain PCBs. Managing potential exposures to PCBs and complying with regulatory requirements are priorities for property managers, and interest has grown about methods for remediation of PCBs in building materials.

Environmental Health & Engineering (EH&E) was retained by the EPA National Risk Management Laboratory to review the literature on remediation methods for PCB-containing building materials. The purpose of this report is to help EPA and other stakeholders identify the approaches in use today to control release of PCBs from building materials, protect public health, and meet regulatory criteria. The review of the literature is not intended as a guide to select the optmal method to remediate PCBs in a particlar buiding, but rather to compile information on the performance of current methods and to provide recommendtons for further development of remediaton methods for PCBs in building materials.

1.1 Scope and Organization of the Literature Review

The scope of this report includes methods for remediation of non-liquid PCBs in building materials, although the topic of liquid PCBs in fluorescent light ballasts is also discussed.

Following terminology suggested by the EPA, *remediation* in the context of this report refers to removing PCBs from building materials or limiting their migration from sources in buildings. The remediation methods are divided into two categories – abatement and mitigation. *Abatement* refers to reducing the amount of PCBs in building materials and more broadly includes remediation methods that involve removing, handling or treating source materials. *Mitigation* refers to controlling exposure to PCBs released from building materials and more broadly includes methods that do not involve handling or direct manipulation of source materials. These working definitions are consistent with the clean-up related terminology suggested by EPA, which is reproduced in Table 1.1.

tabLe 1.1 Definitions of clean-Up Related terms from the U.S. Environmental Protection Agency	
term	definition from ePa
abatement	Reducing the degree or intensity of, or eliminating, pollution
mitigation	Measures taken to reduce adverse impacts on the environment
remediation	1) cleanup or other methods used to remove or contain a toxic spill or hazardous materials from a Superfund site. 2) For the Asbestos Hazardous Emergency Response program, abatement methods including evaluation, repair, enclosure, encapsulation, or removal of greater than 3 linear feet or square feet of asbestos-containing materials from building
Source: EPA, 2011b	

The remediation methods considered in this report are applicable to meeting regulatory standards for PCBs and for managing potential exposures to PCBs in building materials. The methods covered here also include both interim and permanent measures for managing PCBs in buildings.

To gather information on remediation methods within the scope of this review, a comprehensive search was conducted of all publicly available information from peer-reviewed scientific and technical journals, conference proceedings, reports by the U.S. federal and state governments, reports by academic institutions, and reports by international organizations. The search included documents published or released by June, 2011. The documents and resources identified by the literature search were reviewed, culled, and flagged for follow-up searches as warranted. These additional leads were investigated, thereby supplementing the initial list with new documents until a complete survey of the current literature was obtained.

1.2 backGround

PCBs comprise a class of 209 structurally-related chemicals (or congeners) that were widely used as a dielectric fluid in capacitors, transformers, and other electrical equipment beginning as early as 1929 (Rall, 1975). PCBs are well-known human and ecological hazards (ATSDR, 2000). Manufacturing, importation, and most uses of PCBs in the U.S. were prohibited under the Toxic Substances Control Act (15 U.S.C. Sec. 2601 et seq. 1976). Federal regulations that establish authorized uses and disposal practices for PCBs are stated in the Code of Federal Regulations, Title 40, Part 761 (40 CFR §761).

In addition to their use in electrical equipment, over 75 million kilograms of PCBs were reported to have been sold in the U.S. from 1958 through 1971 for use as plasticizers or as a component of numerous industrial products (NIOSH, 1975). These uses of PCBs were in "open-end" applications that include rubbers, synthetic resins, carbonless copy paper, wax extenders, cutting oils, pesticide extenders, inks, textile coatings, and other products (Hesse, 1975; EPA, 1976). Construction materials reported to have been manufactured with PCBs include caulk, adhesives, paints, floor finishes, and other items (see Section 2.3 for additional information). In this report, materials that are known or believed to have been manufactured with PCBs will be referred to as primary sources.

PCBs have also been used as an insulating liquid in ballasts for fluorescent lights. Older light ballasts filled with PCBs continue to be used in some public school buildings. Certain types of ballasts may leak upon reaching the end of their useful life (Staiff et al., 1974), providing a potential source of exposure to PCBs in buildings. Although non-liquid PCBs in building materials is the focus of this literature review, remediation of PCB-containing insulating fluids in light ballasts is discussed briefly.

A large number of buildings may be constructed with PCB-containing materials based on current information about PCB uses in building products. Over 800,000 government and non-government buildings that comprise 12 billion square feet of interior space are estimated to have been constructed between 1958 and 1971 (EIA, 2008). In addition, forty-six percent (46%) of schools in the U.S. (approximately 55,000 schools) are estimated to have been built during that time based on results from a survey of indoor air quality programs in schools (Moglia et al., 2006).

PCBs are persistent in the environment and are known to migrate from primary source materials to adjacent materials in buildings. Elevated concentrations of PCBs have been found in brick, mortar, concrete, foam board, and other items that are adjacent to primary source materials (Coghlan et al., 2002). The upper range of PCB levels in these materials has been reported to be approximately 5,000 ppm. Building materials that accumulate PCBs released from primary sources will be referred to as secondary sources in this report.

PCBs in building materials can also migrate to direct human exposure media including soil, indoor dust, and indoor air. PCB contamination in soil has been reported to extend up to a meter away from building envelopes constructed with PCB-containing caulk (Herrick et al., 2007). Remediation of building-related PCBs in soil has involved excavation of soil to a depth of two feet or more (TRC Environmental, 2010). Further discussion of soil contaminated with building-related PCBs is beyond the scope of this report. Settled dust in buildings constructed with PCB-containing caulk has also been reported to be enriched in PCBs (Chang et al., 2002). Analyses of aggregate exposure to PCBs indicate that indoor air can be the predominant pathway of exposure to PCBs in building materials (EPA, 2009c).

1.3 reGuLatory conteXt

The regulations in 40 CFR§761 define authorized uses of PCBs and types of PCB wastes for both liquid and non-liquid PCBs. The use of PCBs in fluorescent light ballasts notwithstanding, regulations for non-liquid uses of PCBs set forth in 40 CFR§761.3 are of greatest relevance to PCBs in building materials. Because PCBs in building materials are generally not an authorized use according to 40 CFR§761, achieving PCB levels that meet regulatory or risk-based criteria is therefore an important driver of remediation programs for impacted buildings. Background information on these driving forces is provided here; additional information is presented later in Sections 2 and 3.

Once a building material that contains an unauthorized use of PCBs is designated for disposal, the material is subject to classification as either *PCB Bulk Product Waste* or *PCB Remediation Waste*. The definitions of PCB Bulk Product Waste and PCB Remediation Waste are reproduced from

40 CFR§761.3 in Box 1.1. In brief, materials that were manufactured with PCBs, and that contain PCBs at levels equal to or greater than 50 ppm are subject to the requirements for PCB Bulk Product Waste. Materials that contain PCBs as a result of a release from primary sources are subject to the regulations for PCB Remediation Waste. These materials may include waste from clean-up activities, environmental media such as soil, and building components such as concrete and brick. In general, primary sources are typically identified as Bulk Product Waste and secondary sources are commonly determined to be PCB Remediation Waste. However, distinguishing bulk product waste from remediation waste can be challenging for some materials. Additional information on these terms can be found in Box 1.1.

box 1.1 40 cFR §761.3 – Definitions of PcB waste

>> *PCB bulk product waste* means waste derived from manufactured products containing PcBs in a non-liquid state, at any concentration where the concentration at the time of designation for disposal was ≥50 ppm PcBs. PcB bulk product waste does not include PcBs or PcB items regulated for disposal under §761.60(a) through (c), §761.61, §761.63, or §761.64. PcB bulk product waste includes, but is not limited to:

(1) Non-liquid bulk wastes or debris from the demolition of buildings and other man-made structures manufactured, coated, or serviced with PcBs. PcB bulk product waste does not include debris from the demolition of buildings or other man-made structures that is contaminated by spills from regulated PcBs which have not been disposed of, decontaminated, or otherwise cleaned up in accordance with subpart D of this part.

(2) PcB-containing wastes from the shredding of automobiles, household appliances, or industrial appliances.

(3) Plastics (such as plastic insulation from wire or cable; radio, television and computer casings; vehicle parts; or furniture laminates); preformed or molded rubber parts and components; applied dried paints, varnishes, waxes or other similar coatings or sealants; caulking; adhesives; paper; Galbestos; sound deadening or other types of insulation; and felt or fabric products such as gaskets.

(4) Fluorescent light ballasts containing PcBs in the potting material.

>> *PCB remediation waste* means waste containing PcBs as a result of a spill, release, or other unauthorized disposal, at the following concentrations: Materials disposed of prior to April 18, 1978, that are currently at concentrations ≥50 ppm PcBs, regardless of the concentration of the original spill; materials which are currently at any volume or concentration where the original source was ≥500 ppm PcBs beginning on April 18, 1978, or ≥50 ppm PcBs beginning on July 2, 1979; and materials which are currently at any concentration if the PcBs are spilled or released from a source not authorized for use under this part. PcB remediation waste means soil, rags, and other debris generated as a result of any PcB spill cleanup, including, but not limited to:

(1) Environmental media containing PcBs, such as soil and gravel; dredged materials, such as sediments, settled sediment fines, and aqueous decantate from sediment.

(2) Sewage sludge containing < 50 ppm PcBs and not in use according to §761.20(a)(4); PcB sewage sludge; commercial or industrial sludge contaminated as the result of a spill of PcBs including sludges located in or removed from any pollution control device; aqueous decantate from an industrial sludge.

(3) Buildings and other man-made structures (such as concrete floors, wood floors, or walls contaminated from a leaking PcB or PcB-contaminated transformer), porous surfaces, and nonporous surfaces.

Disposal options for PCB Bulk Product Waste and clearance criteria for PCB Remediation Waste designated in 40 CFR§761 are provided in Table 1.2. Options for disposal of Bulk Product Waste include either removal of source materials, decontamination of source materials, or a risk-based disposal method approved by EPA. The criterion for a risk-based approval is that the proposed method will not pose an unreasonable risk of injury to health or the environment.

As shown in Table 1.2, the EPA regulations allow PCB Remediation Waste to be managed according to a method that is termed self-implementing on-site clean and disposal. This disposal options allows residual levels of PCB Remediation Waste to remain in a building. The amount of residual PCBs allowed depends on the use characteristics of the property and the disposition of the PCBs: (i) high occupancy versus low occupancy areas, (ii) bulk concentrations versus surface loading levels, and (iii) unrestricted land use versus a deed restriction. Although not detailed in the table, the regulations for PCB Remediation Waste also allow for performance-based disposal and risk-based disposal methods as approved by EPA.

<table>
<tr><th colspan="5">tabLe 1.2 Summary of Disposal options and clearance criteria for PcB wastes Specified in code of Federal Regulations title 40 Section 761</th></tr>
<tr><th>material</th><th>definition</th><th>disposal options</th><th colspan="2">criteria</th></tr>
<tr><td rowspan="2">Pcb bulk Product waste
40 cfr §761.62</td><td rowspan="2">waste derived from manufactured products in non-liquid state, greater than 50 ppm at the time of disposal. (40 cFR §761.3)</td><td>Performance-based disposal by landfill, incineration or decontamination</td><td colspan="2">RcRA-permitted facility</td></tr>
<tr><td>Risk-based approval</td><td colspan="2">will not pose an unreasonable risk of injury to health or the environment</td></tr>
<tr><td rowspan="8">Pcb remediation waste
40 cfr §761.61(a)</td><td rowspan="8">waste containing PcBs as a result of a spill, release, or other unauthorized disposal. (40 cFR §761.3)</td><td rowspan="8">Self-implementing on-site cleanup and disposal</td><td colspan="2">high-occupancy</td></tr>
<tr><td>bulk</td><td>• ≤1 ppm
• >1 to ≤10 ppm if site covered with appropriate cap (deed restriction)</td></tr>
<tr><td>Porous</td><td>• ≤1 ppm
• >1 to ≤10 ppm if site covered with appropriate cap (deed restriction)</td></tr>
<tr><td>nonporous</td><td>• ≤10 µg/100 cm^2</td></tr>
<tr><td colspan="2">Low-occupancy</td></tr>
<tr><td>bulk</td><td>• ≤25 ppm
• >25 ppm to ≤50 ppm if secured by fence (deed restriction)
• >25 ppm to <100 ppm with appropriate cap (deed restriction)</td></tr>
<tr><td>Porous</td><td>• ≤25 ppm
• >25 ppm to ≤50 ppm if secured by fence (deed restriction)
• >25 ppm to <100 ppm with appropriate cap (deed restriction)</td></tr>
<tr><td>nonporous</td><td>• <100 µg /100 cm^2</td></tr>
</table>

The PCB regulations do not specify a schedule for determination of PCB-containing materials as waste or a timeline for remediation of PCB waste. This aspect of the regulations provides the opportunity for property owners to identify the remediation strategy that is most appropriate for a building with PCB-containing materials. In some cases, conditions warrant control of PCB releases to the environment and the subsequent potential for human exposure while options for permanent remedies are evaluated. Recommendations for methods to control exposure to PCBs in building materials on an interim basis are available from EPA (EPA, 2009b) and are also discussed in Section 3.3 and 3.4.

1.4 enVIronmentaL heaLth conteXt

In addition to accumulating in construction materials through sorption and migration, PCBs that mobilize from building products can also be present in direct human exposure media including soil, indoor dust, and indoor air (Coghlan et al., 2002; Herrick et al., 2007). PCBs in soil and dust are subject to the PCB regulations for bulk product waste and remediation waste however the regulations are silent on limits for PCBs in indoor air of buildings.

Recently, public health targets for school-year average concentrations of PCBs in the indoor air of schools have been suggested by EPA (EPA, 2009c). As shown in Table 1.3, these suggested public health targets range from 70 ng/m^3 for children less than 2 years of age to 600 ng/m^3 for high school students. Site-specific assessments that consider local conditions such as background intake of PCBs, time-location patterns at the school, and the mixture of PCB congeners present in the air have also been used to derive targets for PCB concentrations in indoor air of schools (e.g., MacIntosh et al., 2011).

In some cases, measured concentrations of PCBs in indoor air of buildings with PCB-containing building materials have exceeded the levels suggested by EPA or those derived from site-specific assessments. For instance, indoor air concentrations of total PCBs have been reported to reach 5,000 ng/m^3 in U.S. buildings constructed with PCB-containing materials (TRC Engineers, 2010b). Likewise, concentrations greater than 20,000 ng/m^3 have been reported for buildings in Europe (Liebl et al., 2004; Schwenk et al., 2002). In comparison, PCBs in outdoor air are generally less than 1 ng/m^3 (ATSDR, 2000; Li et al., 2010).

As suggested by the preceding information, PCBs in indoor air can also be a driving force for remediation of PCB-containing building materials, regardless of whether regulatory standards for PCBs in bulk materials are met or not. As described in Section 3, a variety of engineering and administrative controls are available to manage levels of PCBs in indoor air on both a permanent and interim basis.

tabLe 1.3 Public Health targets for PcBs in School Indoor Air (ng/m^3) Suggested by EPA

Age 1-<2 yr	Age 2-<3 yr	Age 3-<6 yr	Age 6-<12yr Elementary School	Age 12-<15 yr Middle School	Age 15-<19 yr High School	Age 19+ Adult
70	70	100	300	450	600	450

Pcb polychlorinated biphenyl ng/m^3 nanograms per cubic meter

* Assuming a background scenario of no significant PcB contamination in building materials and average exposure from other sources, these concentrations should keep total exposure below the reference dose of 20 ng PcB/kg-day.

Source: EPA, 200c

1.5 Summary

PCBs are a class of compounds that had important commercial uses in the U.S. prior to their ban under TSCA due to their association with adverse human and ecological impacts. Primarily used as a dielectric fluid in capacitors, transformers, and other electrical equipment, PCBs were also used as a component of some non-liquid building products including caulking, adhesives, paints, floor finishes, fluorescent light ballasts and other items.

Over 75 million kilograms of PCBs were sold for use as plasticizers or as a component of numerous industrial products from 1958 to 1971, thus, a large number of buildings constructed are at risk of having PCB-containing materials. Understanding available remediation strategies for PCB-containing building materials, therefore, is a critical issue for owners of public and private buildings.

PCBs can be introduced into building materials and media in three primary ways. First, caulk, adhesives, and other products manufactured with PCBs are primary sources of PCBs in buildings. Second, PCBs released from primary sources can accumulate in other building materials over time, creating secondary sources of PCB contamination in a building. Finally, PCBs can be released from primary and secondary sources and subsequently enter indoor air, dust, and soil.

Regulatory standards for PCBs in 40 CFR§761 establish authorized uses, disposal practices, and allowable limits for PCBs in materials. Compliance with the unauthorized use provisions of the regulations is an important driver of remediation programs for PCBs in building materials. Although not addressed in the regulations, PCB concentrations in indoor air of buildings can also be a factor in decisions to control release of PCBs from building materials.

Property owners and managers, regulatory authorities, practitioners, and other stakeholders need information on approaches for managing PCBs in buildings. This report provides a review of literature published on abatement and mitigation of PCBs in building materials. Methods for managing or remediating PCBs in buildings are identified and discussed in the context of the information available on performance, cost, and associated waste.

▶ 2.0 SUMMARY OF LITERATURE SEARCH

In accordance with the statement of work for this contract, a summary of the literature search and results are presented in this section of the report. The summary includes a brief description of the search methodology, a listing of PCB-containing materials identified in the literature, and an overview of the remediation methods discussed in those reports.

2.1 aPProach

To gather information on remediation methods within the scope of this review, a comprehensive search was conducted of all publicly available technical information from peer-reviewed scientific and technical journals, conference proceedings, reports by the U.S. federal and state governments, reports by academic institutions, and reports by international organizations. The search included documents published or released as of June 2011. The documents and resources identified by the searches were reviewed, culled, and flagged for follow-up searches as warranted. These additional leads were investigated, thereby supplementing the initial list with new documents until a complete survey of the current literature was obtained.

The initial literature search on PCB remediation methods focused on peer-reviewed journal articles. The search included electronic indices such as the Science Citation Index, Web of Science, and MedLine (Appendix A, Table A.1). Indices of scientific and technical publications and other electronic resources were queried using multiple keywords representing four search categories; i) chemical, ii) remediation, iii) building type, and iv) building materials. The representative keywords are provided in Table 2.1.

Keywords of the same search category were connected with "OR", and search categories were connected with "AND" in the search. Abstracts for non-English articles were professionally translated into English and evaluated to determine whether the document warranted complete translation.

tabLe 2.1 keywords Used for Literature Search

Search category	keywords
chemical	PcBs, Polychlorinated Biphenyl
mitigation	abatement, encapsulation, excavation, extraction, management, mitigation, modification, remediation, treatment
building type	building, construction, house, residence, school, university
building material	coat, exterior, floor, foam, interior, light ballast, lighting, metal, seal, wall, wire

The grey literature such as white papers, technical reports, and presentations were also searched and included if deemed appropriate. The grey literature search was conducted through web-based search engines, using the key words provided in Table 2.1. In addition, searches of proceedings from relevant scientific conferences were also conducted, including American Conference of Governmental Industrial Hygienists (ACGIH); American Industrial Hygiene Association (AIHA); American Society of Heating, Refrigeration and Air Conditioning Engineers (ASHRAE); American Society for Testing and Materials (ASTM), Air and Waste Management Association (AWMA); International Society for Indoor Air Quality (ISIAQ); Materials Research Society; Society for

Environmental Toxicology and Chemistry (SETAC); International Society for Exposure Science (ISES); International Society for Environmental Epidemiology (ISEE), and the annual Dioxin conference meetings.

2.2 LIterature Search reSuLtS

In total, 92 documents were obtained. These included 11 conference proceedings, 2 PowerPoint presentations, 34 reports of consulting firms and government agencies, 31 peer-reviewed journal articles and 14 websites (Table 2.2). This set of literature identifies a wide variety of building materials reported to contain PCBs, either from the time of manufacture or through sorption over time. Numerous mitigation methods are also discussed in the literature. However, only a small number of these documents also discussed the efficacy or costs of the mitigation methods. Evaluation of performance for any one method is complicated by the fact that multiple mitigation methods are often employed simultaneously to manage risks associated with PCBs in building materials. This management practice limits the ability of the current review to identify precise descriptions of performance for individual methods.

tabLe 2.2 List of References by Literature type

Literature type	number of documents found	references
conference Proceedings	11	chang, 2002; coghlan, 2002; Fragala, 2010; Hamel, 2009; Ljung, 2002; MacIntosh, 2011; Mitchell, 2001; Novaes-card, 2010; Quinn, 2010; Scadden, 2001; tanner, 2010
Power Point Presentations	2	tEI, 2009; vanSchalkwyk, 2009
technical Reports (consulting firms/ Government agencies)	34	Atc, 2010; EH&E, 2011a-b; EH&E, 2010a-f; EH&E, 2007a-b; NIoSH, 1975; NRc, 1976; Ruiz, 2010; SAIc, 1992; tRc Engieers, 2010a-c; tRc Environmental, 2010; EPA, 2010a; EPA, 2007; EPA, 1976; UNEP, 1999; w&c, 2010a-f; w&c, 2009; w&c, 2008a-c; w&c, 2007
Peer-reviewed Journal Articles	31	Andersson, 2004; Blfanz, 1993; Barkley, 1990; Bent, 1994; Bent, 2000; Benthe, 1992; Bleeker, 1999; Broadhurst, 1972; Funakawa, 2002; Gabrio, 2000; Heinzow, 2007; Heinzow, 2004; Hellman, 2001; Herrick, 2010; Herrick, 2007; Herrick, 2004; Jartun, 2009a-b; kohler, 2005; kontsas, 2004; kume, 2008; kuusisto, 2007; Liebl, 2004; MacLeod, 1981; Persson, 2005; Pizarro, 2002; Priha, 2005; Robson, 2010; Rudel, 2008; Schwenk, 2002; Sundahl, 1999
websites	14	cDc, 1987; LPS, 2010; Nyc DoE, 2010; EPA, 2011c; EPA, 2010b-g; EPA, 2009b-c; EPA, 1993; URI, 2001

The remediation methods discussed in these documents focus on primary source materials in buildings, including ceiling tiles, wall paints, and especially sealants. A smaller number of reports discussed mitigation of secondary sources and techniques for mitigating potential exposure to PCBs released from building materials to indoor air. Work plans, an important management tool for remediation programs, were the topic of a few of the reports.

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The remediation methods considered in this report are applicable to meeting regulatory standards for PCBs and for managing potential exposures to PCBs in building materials. The methods covered here also include both interim and permanent measures for managing PCBs in buildings.

The breadth and depth of literature available at this time is consistent with an environmental health topic that has only recently received close attention from the regulatory community and stakeholders in the U.S. The initial notice from EPA regarding PCBs in school buildings was issued in September 2009 (EPA, 2011a), 9 months prior to initiation of the literature search.

2.3 PCB-containing building materials

A wide variety of building materials that contain PCBs are described in peer-reviewed papers and case reports identified by the literature search. Several of the references stress the importance of building inspections to provide a preliminary assessment of the nature and extent of PCB-containing materials, followed by appropriate sampling and analysis of suspect materials and building components (Fragala, 2010; TEI, 2009; W&C, 2008c). This general approach has been demonstrated to be useful for identifying PCB-containing materials, developing inventories of materials that meet criteria for unauthorized uses under the PCB regulations, and source materials that are important contributors to PCBs in indoor air and other pathways of potential exposure. Procedures for building characterization specific to determination of unauthorized use materials are outlined in Subparts N and R of 40 CFR§761. Further treatment of evaluation procedures is outside the scope of this report but should be considered as part of further work.

A list of building materials that have been reported to contain PCBs is provided in Table 2.3. The building materials were grouped according to whether or not they were likely to have been manufactured with PCBs. Building materials manufactured with PCBs would have been part of a broad category of sales for uses that have been termed open-end or open-system applications (EPA, 1976; NRC, 1979). The largest open-end use of PCBs was in plasticizer applications and miscellaneous industrial products (NIOSH, 1975; EPA, 1976). Plasticizers are chemicals added to materials to make them or keep them soft or pliable. Construction products reported to have been manufactured with PCBs include adhesives, caulk, ceiling tiles, paint, and sealants (Broadhurst, 1972; NIOSH, 1975; EPA, 1976; CDC, 1987).

Among measurements of PCBs identified by the literature search, caulk, applied primarily to exterior joints, was the building material most frequently reported to contain PCBs. Caulk also had the highest reported concentration of PCBs with levels commonly in the range of 1,000 to 100,000 ppm and ranging up to approximately 750,000 ppm (ATC, 2010). The mixture of PCBs in caulk most frequently consisted of Aroclor 1254 and Aroclor 1248 (EH&E, 2010f; ATC, 2010; W&C, 2007). Paint and adhesives such as floor tile mastic were also frequently reported to contain PCBs (Bent et al., 1994; TRC Environmental, 2010).

Porous materials such as concrete and brick were frequently reported as secondary sources of PCBs. As noted earlier in this report, porous materials can absorb PCBs when adjacent to caulk or other materials manufactured with elevated concentrations of PCBs (W&C, 2010a; W&C, 2010d; W&C, 2010e; W&C, 2010f; W&C, 2007). PCBs can transfer from secondary sources to other materials as well, including products intended to inhibit migration of PCBs. For instance, silicone caulk applied directly on PCB-containing caulk has been reported to absorb PCBs and in one building eventually reached concentrations up to 4,200 ppm (W&C, 2010c; EH&E, 2007b; W&C, 2010f).

Direct human exposure media, such as indoor air, that have been reported to be impacted by PCBs released from building materials are also noted in Table 2.3.

2.4 remediation methodS

The literature search identified a wide range of remediation methods for PCBs in building materials. Although diverse in purpose and approach, the methods can be grouped according to terminology suggested by the EPA for environmental clean-up activities. The EPA terms that define these groups were presented in Table 1.1.

In this report, *remediation* is an overarching term that encompasses removing PCBs from a building or limiting the migration of PCBs from sources in a building. Two general approaches to remediation are recognized here – abatement and mitigation. *Abatement* refers to reducing the amount of PCBs in building materials. *Mitigation* is a complement to abatement and refers to controlling exposure to PCBs released from building materials without removing PCBs from source materials in a building.

A conceptual framework for organizing the groups of remediation methods is illustrated in Figure 2.1. In this framework, abatement is distinguished from mitigation in that the objective of abatement is to reduce the mass of PCBs or PCB-containing materials in a building, while the objective of mitigation is to limit release of PCBs from building materials or their transfer to the environment and locations where people may be exposed. Abatement activities involve handling, treating, or directly contacting PCB-containing materials in a manner that removes primary and secondary source materials from a building or lowers the amount of PCBs in building materials through chemical degradation or extraction techniques. Mitigation actions do not involve modifying source materials, but instead may be intended to block pathways of PCB transport, dilute concentrations of PCBs in exposure media, or establish uses of building space that minimize exposure to building-related PCBs.

Details of the various remediation methods are described in Section 3 and a brief summary of individual remediation methods are provided in Table 2.3.

2.4.1 abatement

In general, abatement methods are intended to provide a permanent remedy to unauthorized or undesired uses of PCBs in building materials. A permanent remedy can be achieved by removing PCB-containing materials from a building or reducing the amount of PCBs in a material below the clearance criteria for residual PCBs as defined in 40 CFR§761 (see Table 1.2). A summary of information identified on abatement achieved by source removal and source modification methods follows.

tabLe 2.3 PcB containing Building Materials and Exposure Media		
material	maximum concentration from buildings	references reporting Pcb contaminated materials
Primary Source material (possibly manufactured with Pcb)		
caulking (Sealant, Plaster)	959 – 752,000 ppm	(a), (b), (d), (e), (f), (g), (i), (j), (k), (l), (q), (r), (t), (w), (aa), (bb), (cc), (ff), (ii), (jj), (kk), (ll), (mm), (nn)
Adhesives/Mastic	3.9 – 3,100 ppm	(d), (e), (g), (l), (hh), (ii), (jj)
Surface coating	140 – 255 ppm	(d), (g), (dd), (ii)
Paint	0.7 – 89,000 ppm	(a), (e), (g), (h), (u), (v), (y), (hh), (ii)
ceiling tiles	57 – 51,000 ppm	(g),(h),(l)
Glazing	Up to 100% liquid PcB	(l), (jj)
Light Ballast	1,200,000 ppm	(m)
Electric wiring	14 ppm	(g)
Secondary Source material (probably not manufactured with Pcb)		
Insulation Materials	0.2 – 310 ppm	(b), (i), (l), (ee), (hh)
Backer Rod	99,000 ppm	(b)
Gaskets	4,300 ppm	(i)
cove Base	170 ppm	(l)
Polyurethane foam (furniture)	47 – 50 ppm	(g),(ii)
wood	380 ppm	(g)
Brick/Mortar/cinder Block	2.8 – 1,100 ppm	(b), (l), (y), (kk)
Asphalt	140 ppm	(k)
Stone (granite, limestone, marble, etc.)	130 ppm	(ll), (mm), (nn)
concrete	53 – 17,000 ppm	(b), (e), (g), (k), (v), (y), (ff), (kk), (mm), (nn)
non-Porous materials		
Metals Surfaces	48 μg/100 cm^2	(g),(k),(kk)
Door Frame	102 ppm	(hh)
Railing	70 ppm	(hh)
exposure media		
Soil/Sediment/Sand	0.1 – 581 ppm	(a), (l), (s), (u), (bb), (kk), (ll), (mm), (nn)
Settled Dust	120 μg/100 cm^2, <1.5 - 190 ppm	(l), (dd), (jj)
Indoor Air	35 – 24,000 ng/m^3	(c), (d), (e), (f), (i), (j), (l), (n), (o), (p), (w), (x), (y), (z), (ee), (ff), (gg), (ii)

references

(a) Andersson, 2004
(b) Atc, 2010
(c) Balfanz, 1993
(d) Bent, 1994
(e) Bent, 2000
(f) Benthe, 1992
(g) Bleeker, 1999
(h) cDc, 1987
(i) chang, 2002
(j) Gabrio, 2000
(k) EH&E, 2007b
(l) EH&E, 2010f
(m) EPA, 2011c
(n) Funakawa, 2002
(o) Heinzow, 2004
(p) Heinzow, 2007
(q) Hellman, 2001
(r) Herrick, 2004
(s) Herrick, 2007
(t) Herrick, 2010
(u) Jartun, 2009a
(v) Jartun, 2009b
(w) kohler, 2005
(x) kontsas, 2004
(y) kuusisto, 2007
(z) Liebl, 2004
(aa) Persson, 2005
(bb) Priha, 2005
(cc) Robson, 2010
(dd) Rudel, 2008
(ee) Schwenk, 2002
(ff) Sundahl, 1999
(gg) tRc Engineers, 2010b
(hh) tRc Engineers, 2010a
(ii) tRc Environmental, 2010
(jj) URI, 2001
(kk) w&c, 2007
(ll) w&c, 2010a
(mm) w&c, 2010c
(nn) w&c, 2010e-f

As shown in Figure 2.1, source removal methods include physical removal and on-site decontamination of PCB-containing materials. Physical removal involves displacement of bulk material that contains PCBs followed by disposal according to applicable state and federal regulations. In the case of PCB caulking, hand tools such as utility knife, putty knife, scraper, ripping chisel, and bush hammer are typically used to pry beads of caulk from the seams in manageable lengths. Various types of abrasive blasting techniques are physical removal methods that have been applied to surface coatings that contain elevated concentrations of PCBs. In both cases, the removed caulk or surface coating is placed in sealed containers which are stored in a covered roll-off and subsequently disposed of as hazardous waste.

In addition to physical removal of PCB-containing materials, source removal can also be achieved through on-site decontamination. Several products and techniques for chemical degradation of PCBs in bulk product waste and remediation waste materials are described in the literature. In general, the products are applied to PCB-containing materials as a slurry or paste, covered by an overlying material, and left in place for days to weeks as required by the kinetics of the degradation reactions. Spent product and degradation products are waste byproducts of the process.

Old fluorescent light ballasts that were manufactured with PCBs remain in use in some buildings and their remediation constitutes a special case of source removal. Detailed source removal procedures (clean-up and decontamination) for a leak, including management and disposal of wastes from PCB-containing ballasts, are outlined in the PCB regulations and summarized in Section 3.

fIGure 2.1 Framework for Methods to Remediate PcBs in Building Materials

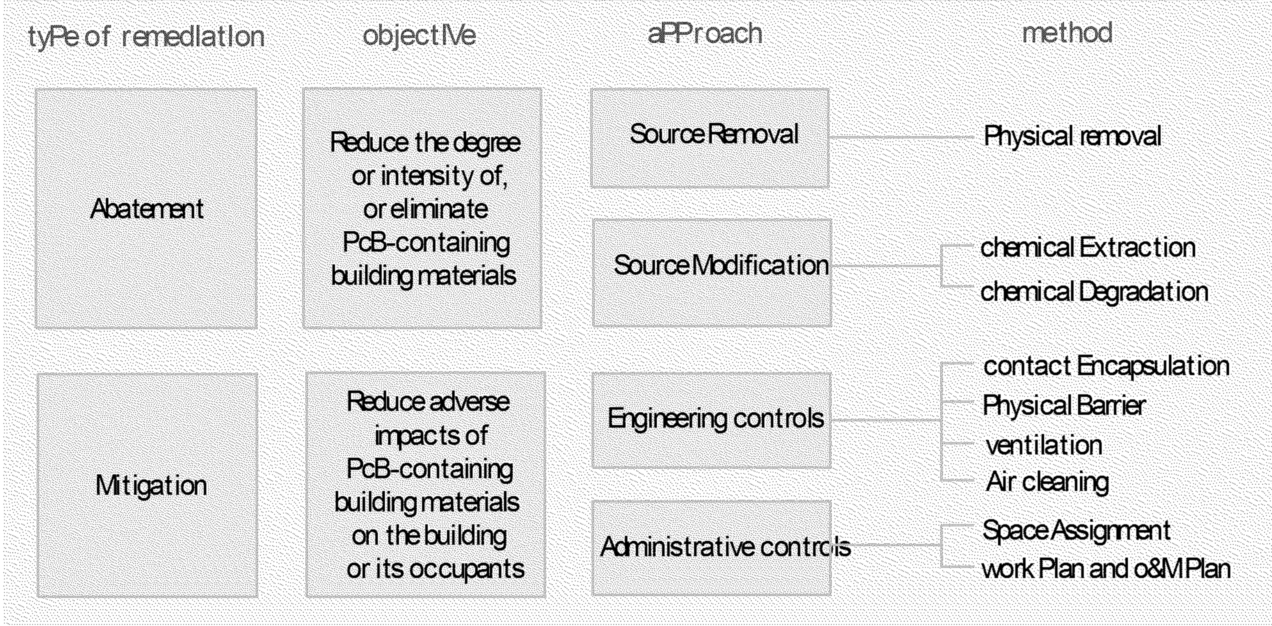


tabLe 2.4 Description of Remediation Methods			
remediation method	approach	method	description
abatement	Source Removal	Physical Removal	Remove PcB-containing building materials using hand or mechanical tools
	Source Modification	chemical Extraction	Apply a solvent that washes PcBs from building materials
		chemical Degradation	Treat building materials with a chemical product that at transforms PCBs into less hazardous substances
mitigation	Engineering controls	Encapsulation	Apply a low permeability film or sealant directly to PcB-containing materials
		Physical Barrier	Separate PcB-containing materials from other (e.g., occupied) areas of a building
		ventilation	Deliver PcB-free air to the interior of a building to control PcB concentrations in indoor air
		Air cleaning	operate a fan-operated device equipped with activated charcoal or other filtration media for which PcBs have high affinity
	Administrative controls	Space Assignment	Use risk-based criteria to assign space to occupants of a building
		work Plan and o&M Plan	Implement procedures and policies that detail how PcBs in building materials will be managed so as not to present an unreasonable risk of injury to health or the environment

2.4.2 mitigation

Mitigation generally refers to controlling impacts of building material-related PCBs without actually removing PCBs from source materials. Mitigation methods can provide interim measures of control such that PCBs in building material do not pose an unreasonable risk of injury to human health and the environment. Accordingly, interim measures are typically planned and implemented to provide an equivalent level of protection to permanent measures. Mitigation methods can also be a component of activity undertaken following an abatement action or as part of a management in place program for residual PCBs in building materials.

As described below, engineering and administrative controls implemented alone or in combination can be effective at mitigating releases of PCBs to the environment and limiting exposure.

Engineering Controls

Engineering controls involve changes to the physical conditions of a building that reduce the magnitude of potential uncontrolled releases of PCBs and corresponding exposure. These controls can take many forms but are principally contact encapsulation; physical barriers; ventilation; and air cleaning.

Contact encapsulation refers to covering PCB-containing materials with an impermeable film or sealant. The sealant serves to reduce potential for dermal contact with PCBs and to retard release of PCB-containing materials or PCBs through weathering, mechanical degradation, or volatilization.

Contact encapsulation is described in the literature as a mitigation method for PCB-containing caulk, paint, adhesive, and other materials. Numerous encapsulants are described in the literature and include certain types of tape, sealants, and epoxies. Details about these methods are provided in Section 3.3.1.

Physical barriers constructed to separate areas with PCB-containing building materials from other areas of a building are another type of engineering control. In some cases, physical barriers such as fences and interior walls can be erected to prevent building occupants from coming into direct contact with PCB-containing building materials. For example a simple plastic mesh snow fence can be placed around the perimeter of a building façade to prevent people from approaching or contacting PCB-containing caulk or paint on the exterior face of the building. In other cases, physical barriers can be used to minimize transport of PCB vapors from source materials to occupied areas of a building. Barriers to control vapor transport include sealants or foam applied to joints of building features that form interstitial spaces which include PCB-containing materials. Examples of interstitial spaces that may enclose PCB-containing materials include aluminum framing around the panels of a curtain wall sealed with PCB caulk or wallboard covers over structural beams that are sealed with PCB caulk.

Ventilation with outdoor air and cleaning of indoor air are engineering controls that can be used to modify concentrations of PCBs in indoor air that are associated with volatilization from PCB-containing materials. Improvements or upgrades to existing ventilation systems have been shown to be effective at lowering concentrations of PCBs in indoor air. However, the cost of heating and cooling outdoor air can be a practical constraint on implementation of this mitigation method. Operation of air cleaners equipped with activated charcoal filters was described as effective at lowering PCB levels in indoor air in one report identified by the literature search (EH&E, 2010c). Additional research is needed to evaluate the role of air cleaning as a long-term remedy for managing exposures to building-related PCBs.

Administrative Controls

Administrative controls involve changes to the use or maintenance of a building that reduce the magnitude of potential occupant exposures to PCBs or the likelihood of uncontrolled releases of PCBs from source materials. A space assignment plan that places building occupants in locations that yield exposures below established targets for indoor air or other media is an example of an administrative control. Similarly, adoption of an operation and maintenance plan for residual PCBs in building materials as part of an overall facility management program can be effective at confirming the continued performance of other remediation methods. As described in Section 3, the parameters of administrative controls can be informed by a site-specific assessment of PCB exposure and risk.

The literature search also identified work plans as an important form of administrative control. Work plans are designed to ensure that remediation efforts comply with all applicable rules and regulations and that the planned remediation activities do not pose an unreasonable risk of injury to human health and the environment.

Work plans are necessarily site-specific, yet all work plans strive to ensure consistent and effective management of a remediation action for PCB-containing building materials. Specification of the flow of work is critical for containment of PCBs during remediation. The work flow for a project typically includes: site protection and isolation, source removal, surface cleaning, material decontamination, inspection and testing of non-porous surfaces, source modification, testing and verification, site restoration, project acceptance, and completion.

The key elements of a typical work plan for remediation of PCB-containing building materials are provided in Table 2.5. The remediation methods described in Section 3 would typically appear prominently in sections of a work plan that address scope, schedule, and procedures. More detailed information on the major components of work plans is presented in Section 3.4.2.

Applicability of Mitigation Methods

Mitigation of impacts arising from PCBs in building materials rather than abatement of the PCB-containing materials strikes a balance among (i) disruption of building operations, (ii) cost of abatement, (iii) regulatory requirements and (iv) risk to health and the environment.

Disruption associated with abatement of PCB-containing building materials can favor mitigation over abatement. As described in Sections 3.1, methods commonly used to remove or modify PCB-containing materials can involve construction practices that generate noise, dust, gases, and require involved containment procedures similar to those used for asbestos. Destructive procedures for removing concrete, brick, mortar, and other substrates that have absorbed PCBs from source material such as caulk are often the most disruptive. Abatement activities are often undertaken most efficiently in unoccupied areas of a building and may require the relocation of building occupants. Disruption of building operations may be greatest when a temporary space for use by building occupants, i.e., swing space, is not available. Therefore, mitigation approaches that limit exposure to PCBs in building materials can help organizations maintain business continuity and control costs.

tabLe 2.5 key Elements of a typical work Plan for Mitigation of PcB-containing Building Materials	
case nar rative	Description of the building, presentation of PcBs in building materials, and overview of abatement goals
regulations, Permits, and Qualifications	Identification of applicable regulations and corresponding permits and certifications required to perform the abatement plan
Scope and Schedule	Identification of materials to be abated, overview of mitigation methods, and forecast of work schedule
execution Plan	Description of work flow ranging from site preparations through disposal
abatement Procedures	Detailed description of procedures for source removal, source modification and, if planned, management options
Storage and disposal	Statement of plans for storage and disposal of PcB bulk product and remediation waste
abatement completion acceptance criteria	Identification of performance criteria and evaluation procedures for the mitigation actions
health and Safety	Plan to ensure health and safety of abatement contractors, visitors to the site, and occupants of the building

As shown in Table 1.2, the regulatory framework for PCBs includes risk-based approvals that appear to allow PCB-containing materials to be managed in place on a temporary basis. Based on information identified by the literature search, risk-based approvals are made on a case-by-case basis and follow the generally accepted procedures for quantitative analyses of cancer and non-cancer risks for PCBs.

The extent of health risk posed by leaving PCB-containing materials in place for a pre-defined period of time is a core consideration in a decision about the degree to engage in abatement or mitigation. The potential for direct contact with PCB bulk product waste or other PCB-containing materials should be part of any such decision. PCB-containing materials in building facades above ground-level often present limited opportunity for direct contact in most cases and may be amenable to mitigation. As noted earlier in this section, physical barriers can prevent direct contact with PCBs in building materials at ground level or indoors. Physical barriers can limit transfer of PCB vapors to indoor locations as well. A mitigation program can also include ventilation strategies to transfer PCBs from indoor air to outdoor air and thereby control inhalation exposures indoors.

The response to discovery of PCB-containing materials in an elementary school provides an illustrative example of mitigation as an interim remedy (EH&E, 2010a-f). The construction of the approximately 65,000 square foot, single story building in 1961 included curtain walls that contained composite panels held within aluminum framing by PCB-containing caulk. Approximately 500 linear feet of caulk was exposed along both the interior and exterior face of the composite panels in each classroom. Potential pathways of exposure to PCBs associated with the caulk included direct contact with caulk inside and outside of the building as well as inhalation of PCBs volatilized to indoor air. Children under 6 years old were moved to classrooms in a masonry addition of the school without PCB-containing materials. Physical barriers, including bi-layer sealants, gypsum board walls, and fences constructed over the interior and exterior caulk, prevented direct contact with the PCB-containing material. Modifications to the ventilation system led to further control of PCB levels in indoor air. Abatement activities were undertaken primarily when school was not in session in order to minimize disruption of education. As a result of these combined efforts, residual PCB exposures were brought below risk-based tolerances, disruption of the educational mission was minimized, and costs were controlled without removing the source material or demolishing and rebuilding large portions of the building.

3.0 remediation methods

The literature search identified a wide range of manual, mechanical, chemical, engineering, and management techniques to effect source removal, source modification, and control of PCB exposure. Each method is described in the remainder of this section following the framework for remediation methods presented in Section 2.4. Where available, information on performance and cost is provided as well.

3.1 Source remoVaL

3.1.1 Physical removal of bulk materials

Physical removal methods involve the direct removal of PCB-contaminated materials. Physical removal is often the remediation approach of choice for caulk, porous materials (e.g., concrete, bricks), paints, ceiling tiles, and other bulk materials. Physical removal is generally recognized as an effective remediation measure, and can be performed using manual or mechanical techniques. A summary of physical removal methods for bulk materials is provided in Table 3.1.

Manual methods are based on direct handling of PCB-containing materials by abatement contractors or the use of hand tools. Manual methods are often favored over mechanical methods because they typically produce substantially lower emissions of dust and debris, noise, vibration, and odor (VanSchalkwyk, 2009). Manual methods are most applicable to discrete building materials that are not chemically bonded to adjacent materials. For example, manual removal is often the first step in abatement of PCB-containing caulk from around the exterior of window frames and between concrete panels. Hand tools and direct manipulation are also useful for removing certain materials that may absorb PCBs over time such as foam insulation, cove base, and ceiling tiles. In contrast, manual removal methods are less amenable to PCB-containing films such as paint. A photograph of abatement contractors in appropriate protective measures during remediation work is presented in Figure 3.1.

fIGure 3.1 Photograph of PcB-containing caulk Removal Using Hand tools

Source: ePa, 2010d

Direct bulk removal for PCB-containing paint can include the complete removal of all wallboard that has been painted. For cases where the paint cannot be removed without damaging the structural stability of the external wall, a "false wall" can be constructed over these painted external walls to prevent any direct contact with the existing tabLe 3.1 SourceRemoval Methods for Abatement of PcB-containing Building Materials

method	description	example	applied building materials	references*
Bulk removal	Remove using hand tools	utility knife, scraper, ripping chisel, putty knife, bush hammer, hammer and chisel	caulk, porous materials (concrete, brick, granite), non-porous materials (metal), soil, paint	(a), (b), (c), (d), (e), (f), (g), (h), (i), (j)
Sandblasting	Most commonly used techniques where PcB contamination is limited to the upper 0.5 centimeters of porous media such as concrete. Sandblasting involves blasting fine grains of abrasive sand onto the PcB contaminated surface to strip away surface coatings and remove the porous material below. Shot blasting involves shooting varying sizes of metal shot against the surface and is more effective at bulk material removal. the shot is recovered in the process using a specially fitted vacuum system that separates the shot from PcB-contaminated residue.		Paint, concrete	(k), (l), (e)
Shot blasting				(k)
Bead blasting	Process of removing surface deposits by applying fine glass beads at a high pressure without damaging the surface.		concrete	(e)
Hydro blasting	Use high pressure (i.e. 1,000 to 6,000 pounds per sq inch) washing of building walls, ceilings, and equipment surfaces. High pressure water is sprayed against the PcB contaminated surfaces, and the wash water is then collected and disposed of. Hydro blasting can be especially effective for removing paint and coating layers. Under very high pressure it can also be used to cut and remove porous media such as concrete, but is generally less effective and results in more waste (i.e. contaminated water) than other available methods.		Paint, concrete	(e), (k)
co$_2$ blasting	Pellets of frozen co$_2$ are blasted against the affected surface.		Paint, caulk	(h), (j), (k)
Scarification	Scarifying and scabbling are more applicable where PcBs extend deeper into the porous material (i.e., 1 to 5 cm penetration in concrete). Scarifiers contain a helical rotating cutting tool that is attached to a tractor or large mobile roller and used to remove a layer of concrete. Scabblers use small, high-pressure impact pistons to sequentially break up the concrete. Scabblers are generally smaller than scarifying units and have a lower concrete removal rate, but scabblers are more adaptable to different indoor environments. Both devices are able to shave off from 1/16 inch to 1/8 inch of concrete per pass.		concrete	(b), (k),(m)
Scabblers				(k), (m)
Saw cutting	Process of controlled sawing, drilling, and removal of concrete using special saws that use diamond impregnated blades. cutting leaves a smooth finish and utilizes water so as to not create any dust.		concrete, caulk	(b), (c), (j), (m),
Grinders	Use horizontally rotating discs to level, smooth or clean the top surface of a concrete slab. Grinders provide contractors with a smoother finish than scarifiers or scabblers.		concrete	(c)
Roto-peening	Portable tool designed to remove and descale protective coatings from steel, concrete, brick, and wood.		concrete	(e)

References:

a) tRc Environmental, 2010
b) tEI, 2009
c) Sundahl, 1999
d) EH&E, 2007a-b
e) w&c, 2009
f) w&c, 2010a-f
g) EH&E, 2010f
h) Bent, 1994
i) Bent, 2000
j) EPA, 2010g
k) Mitchell, 2001
l) kuusisto, 2001
m) Hamel, 2009

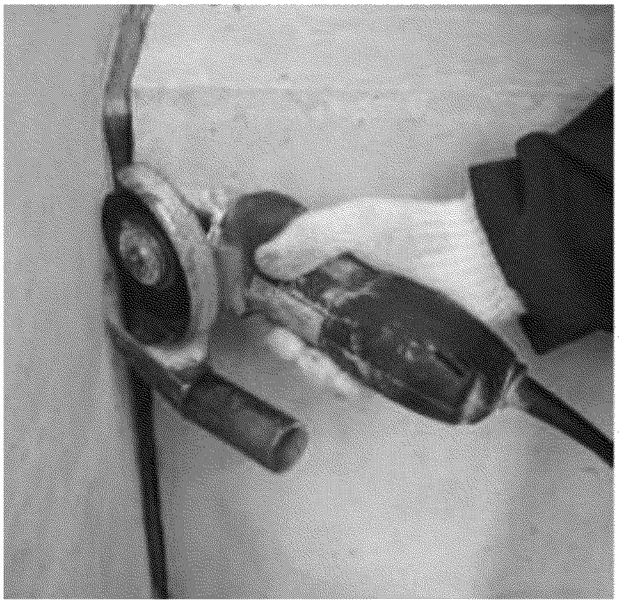
painted surface (TRC Environmental, 2010). Information on other approaches to physical barriers is provided in Section 3.3.

Mechanical methods of bulk removal include hammer drill or saw cutting, scarification, sand blasting, bead blasting, and water blasting, with the specific method selected dependent on the contaminated material (TEI, 2009). Removal processes that involve large power tools, such as blasting, can be problematic, resulting in notable noise, vibration, odor, and inconvenience. To address these limitations, VanSchalkwyk (2009) advocated relying upon material removal with hand tools, including caulking removal, aided by chemical washing of only horizontal surfaces, and encapsulation of all adjacent building surfaces. For caulk, direct bulk removal requires the removal of caulk within joints and seams and, if necessary, in the adjacent building materials. The cost estimate of caulk removal exceeds $100/linear foot of caulk (VanSchalkwyk, 2009).

Selection of the most appropriate tools for caulk removal is based on caulk properties, location, and accessibility. EPA categorizes caulk into two types: (i) hard and brittle which is typical of aged and weather exposed caulks and frequently seen in exterior areas, or (ii) elastic and soft, which is found primarily in areas protected from sunlight and weather, and located indoors (EPA, 2010c-f). Material and conditions of the adjoining structures are key elements to consider in choosing an appropriate tool for removal of caulk. Anticipated dust and heat generation also plays an important role in selecting the appropriate tool and method. A summary of tools and methods for removing caulk prepared by EPA is provided in Table 3.2.

Mitigation of PCBs in secondary source materials such as brick or concrete can be more challenging and substantially more expensive than removal of caulk and other primary source materials. This situation is illustrated by a building in which concrete that was adjacent to beads of PCB-containing caulk was found to contain unauthorized PCB levels. Concrete in the immediate vicinity of the caulk was identified as PCB Remediation Waste and designated for removal and disposal. At this building, a ½-inch by ½-inch linear section of concrete was removed from both sides of every seam between concrete panels that formed the façade of the 17-story structure. The concrete sections were removed with hand-held circular grinding tools operated by trained laborers (see Figure 3.2). Approximately 18 miles of ¼ square inch concrete sections were removed from the face of the building. A hand-held HEPA vacuum was used to capture dust generated by the cutting tools. Personal protective equipment including

fIGure 3.2 Removal of concrete Adjacent to Former Seam of PcB caulking Laid Between Pre-formed concrete Panels



(Source: Fragala, 2010)

table 3.2 Summary of tools and Methods for caulk Removal				
tools/method	Suitability	advantages	disadvantages	Protective measures to consider
mechanical tools				
utility knife	• Universally applicable tool, especially for cutting out elastic and soft caulk together with an electrical joint cutter • Suitable for all smooth joint faces • Less suitable for working on projects with caulk of lengths exceeding 100 m • Less suitable for very hard caulk • choice of different blades to suit the joint width and depth	• Short, sturdy blade that is easily exchangeable • Handy, low weight • No dust development in case of elastic caulk • Little dust when removing slightly brittle caulk and cleaning joint faces • Gentle treatment of joint faces	• Requires great exertion in case of hard caulk • Relative low output (linear meters of caulk/hour) • Relatively high labor costs	• General personal protective measures • construction of containment Area enclosure (if dust is generated) • work area decontamination
ripping chisel	• Suitable for breaking out or chiseling hard caulk, especially when working with joint in concave angled planes • Less suitable for joints with a width of less than 5 mm • Less suitable for working on projects with caulk of lengths exceeding 100 m	• Removal of hard and brittle caulk: the cutting edge can be moved along the joint face with greater pressure than a utility knife • Low dust development in case of rough joint faces	• Quickly dulls when working with rough joint faces made of concrete or other hard materials • Possible damage to adjoining structural parts	• General personal protective measures • construction of containment Area enclosure • Dust aspiration at the source when cleaning joint faces/ removing loose or crumbling caulk as described in Abatement Step 2
Putty knife/scraper	• Suitable for reworking joint faces with shaving or scraping • Suitable for removing loose or crumbling caulk	• Suitable for rough joint faces	• Poor cutting action • Small particle debris at the joint faces • Longer joints and hard caulk	
bush hammer	• Suitable for hammering away hard or well-attached caulk residue on hard, robust areas	• No heavy dust development	• Limited to hard and solid surfaces	
hammer and chisel	• Suitable for very hard, brittle, or wide joints > 2 cm	• For very hard caulk	• Possible damage to structural parts	

tabLe 3.2 *Continued*				
tools/method	Suitability	advantages	disadvantages	Protective measures to consider
eLectromechanIcaL tooLS				
electrical joint cutter with oscillating blade	• Universally applicable tool for cutting out hard and soft caulk, especially in combi nation with a utility knife; suitable for all material types of adjoining structures. • Less suitable for removing caulk that is difficult to access • Not suitable for very hard caulk	• Short, sturdy blade that is easily ex-changeable • Handy, acceptable weight • Low dust volume • typically low risk of damage to joint faces with careful work	• Moderate exer tion required • No integrated dust aspira-tion	• General personal protective measures • construction of contain-ment Area enclosure • Maintain negative air pressure with induced draft fan equipped with High Efficiency Particulate Air (HEPA) filters • Dust aspiration at the source when removing loose or crumbling caulk/ cleaning joint faces as described in Abatement Step 2
electrical scraper with exchangeable blades	• Universally applicable tool for cutting out hard and soft caulk, especially in combi-nation with a utility knife • Suitable for difficult-to-access joint areas in corners and along edges • Also suitable for reworking joint faces • Not suitable for very hard caulk	• Lightweight device, handy • Low exertion • Low dust volume	• No integrated dust aspira-tion	
needle hammer	• on level areas: for broad, shallow dummy joints and connections joints	• Removal of firmly at-tached, hard caulk	• Higher dust volume; pos-sible damage to adjoining structures	
rotary cutting tools	• only suitable for cutting out the caulk • Not suitable for reworking joint faces • Suitable for difficult-to-access joint areas long edges; not suitable for accessing corners	• Lightweight device, handy • Low exertion • typically low risk of damage to joint faces with careful work	• Higher dust volume • No integrated dust aspira-tion	
jigsaw with exchangeable saw blades	• tool with integrated dust aspiration. Use is limited to deep joints with free space in accordance with blade length • only suitable for cutting out the caulk • Not suitable for reworking joint faces • Not suitable for difficult-to access joint areas in corners and along edges	• Good cutting rate for semi-soft and hard caulk • Integrated dust aspiration	• only suitable for joints in vertical planes with open joint backup	• General personal protective measures • construction of contain-ment Area enclosure • Maintain negative air pres-sure with induced draft fan equipped with HEPA filters • connection of the integrat-ed dust aspiration device to an industrial vacuum with HEPA filters.
diamond sanding device	• Electrical joint cutter with oscillating, diamond-coated cleaning and blade and integrated dust aspiration • only suitable for cleaning joint faces	• Low dust volume compared to angle grinder • Integrated dust aspiration	• Heat develop-ment and gas-eous emission production not clarified	

table 3.2 *Continued*				
tools/method	Suitability	advantages	disadvantages	Protective measures to consider
chemical-Physical methods				
dry ice (CO_2) blasting	• Suitable for gentle reworking of joint faces • Suitable for large joint lengths	• Gentle on the surrounding materials • Good cleaning performance (Note: In some cases, the method cannot completely remove caulk) • Good performance for large joint lengths	• Expensive (especially in combination with high demands for protective measures) • complex requirements for protective measures	• Enclosure of the work area with airtight seal, negative pressure and controlled air exchange, dust aspiration at the source • Full respirator with fresh air supply and protective suit • Noise and ear protection (noise levels range from 85 to 120 dBA, depending on the device)
Source: EPA, 2010g				

full body clothing and N95 respirators was also used to limit PCB exposure to workers (EH&E, 2007a–b). The cost of the abatement project was approximately $1.4 million, which equated to $9 per square foot of the building and $30 per linear foot of PCB-containing caulk. Other project-related costs, both hard and soft costs, included characterization of PCB-containing materials, disruption of building operations, and disposal of the PCB Bulk and Remediation Waste.

Documents identified in the literature search offered little information on the costs of physical removal methods for bulk materials. However, the costs of removing exterior PCB caulk and contaminated porous materials, primarily concrete, using hand and mechanical tools was reported for four buildings (Fragala, 2010). As shown in Table 3.3, the remediation cost generally increased as the size of the building increased. The cost normalized to building size ranged between $9 to $18 per square foot of indoor building space. The variation in costs reflects many factors including the amount and accessibility of PCB-contaminated building materials.

The impact of direct bulk removal on PCB concentrations and potential exposures for occupants and abatement workers was discussed in two peer-reviewed papers identified by the literature search. Sundahl (1999) examined PCB concentrations in work site air before and during remediation of PCB-containing caulk between cement blocks. The abatement process consisted of several steps: (1) cutting the elastic sealant with an oscillating knife, (2) grinding the concrete with a machine, (3) sawing the concrete with a mechanical saw, and (4) cutting the concrete with a mechanical chisel. Each process was performed together with a high capacity vacuum cleaner connected to each of the tools. The authors reported that PCBs accounted for up to 8% of the sealant by weight. PCB concentrations up to 450 ppm were found in the surrounding concrete. Without proper controls, PCB concentrations in indoor air were elevated during remediation, with levels generally above the occupational exposure limit of 10 $\mu g/m^3$ and sometimes over ten times higher (120 $\mu g/m^3$). However, PCB levels in air were below the occupational exposure limit when proper controls for dust and gases were in place.

tabLe 3.3 Remediation costs Reported by EH&E				
building type	work Schedule	building Size (Square feet)	remediation cost ($)	cost per square foot
University Academic	vacated due to occupant fears	80,000	$1.4 Million	$18
commercial office	occupied	260,000	$3.4 Million	$13
University office	Unoccupied	155,000	$1.4 Million	$9
University Academic	occupied	197,000	$2.4 Million	$12
Source: Fragala, 2010				

Similarly, Kuusisto (2007) analyzed PCB concentrations on building surfaces after PCB-containing paint was sandblasted with silica and estimated corresponding health risks from these concentrations. A total of sixteen wipe samples were collected after sandblasting was performed in two Finnish industrial buildings. Airborne PCB concentrations were also measured for two hour periods using active samplers. The total surface PCB concentrations ranged between 100 and 1,100 μg/m^2. Estimated cancer risks were higher for children (1.2 x 10^{-4}) as compared to adults and occupational workers (1.3 x 10^{-5} and 1.5 x 10^{-5}, respectively). The hazard quotients, a characterization of non-cancer risk, ranged between 3.3 and 35 depending on the exposure scenario. Acceptable surface concentrations (e.g., protective for 95% of the exposed population) were calculated to equal 7 μg/m^2 for residential use, 65 μg/m^2 for adult residential use, and 140 μg/m^2 for occupational use. Pilot cleanup experiments showed that PCB-contaminated surface dust should be removed with industrial vacuum cleaners and washed with terpene containing liquid, as vacuuming alone did not sufficiently clean surfaces to acceptable risk levels.

Papers and reports identified by the literature search indicate clearly that physical removal methods are rarely used in isolation and their efficacy is rarely assessed in the absence of effects that are attributable at least in part to complementary mitigation methods. This observation is illustrated by the synopsis of a mitigation effort described by Bent et al. (1994, 2000) that is presented in Box 3.1.

The majority of peer-reviewed scientific papers identified by the literature search focused on characterizing PCB exposures for abatement workers. Several of these studies were based on occupational cohorts in Finland. Priha et al. (2005), for example, conducted a study to assess PCB exposures and health risks among Finnish workers at nine remediation sites. As part of their job, workers operated grinding wheels with local exhaust units for one to four hours while wearing respirators. Personal PCB samples were collected from the breathing zone of 14 workers, while PCB concentrations in 27 elastic sealant samples from nine buildings were also measured. Exposures were estimated using standard algorithms to calculate lifetime average daily dose and carcinogenic risk. The authors found that the estimated PCB exposures of workers were higher than those of the general population, with exposures 10-fold higher than the reference dose and average dietary intake. The calculated point estimate of excess cancer risk was 4.6×10^{-4} cancer cases per lifetime. Since exposure and risk calculations did not account for the fact that workers wore respirators, however, it is likely that risk calculations overestimated exposure and risk.

box 3.1 Mitigation Efforts Described by Bent et al. (1994, 2000)

In a paper by Bent et al. (2000), a mechanical approach to mitigation of PcB-containing paint was carried out in the remediation of a German school building with PcB concentrations in indoor air of classrooms ranging from 6,000 – 7,000 ng/m^3. PcBs were present in the indoor and outdoor faces of concrete, paints, heating element paints, ceiling tiles, and floor surfaces. A total of 245 material samples were collected from remediated and control rooms, with samples from similar sources and room types combined. one hundred material samples were analyzed for PcB contamination. tests of 30 samples showed that 90% of the casing joints had PcB concentrations of at least 50,600 milligrams per kilograms (mg/kg), with an average value of 85,522 $\pm$ 13,863) mg/kg. the average value for other materials was lower. For example, wall paints had an average value of 216.3 $\pm$ 82.0) mg/kg. Factors such as temperature were found to affect PcB levels in air.

Primary surfaces, including the casing joints, heating element paints, and ceiling tiles, were removed manually with cutting tools. Secondary contaminated surfaces were decontaminated using a high-pressure water method, which delivered water at a pressure of up to 2x10^8 pascal to abrade PcB-contaminated surfaces. Resulting PcB-containing sludge was disposed directly in a hazardous waste landfill. Following removal of primary and secondary sources, remediated areas were ventilated (air exchange rates >5 per hour) and basic cleaning was performed. together, these methods led to the successful reduction of PcB concentrations in ambient air to below 600 ng/m^3. of note, a thermal diffusion method was also tested as a method to remove PcBs from secondary contaminated surfaces. However, this method was found to be ineffective.

In the case study by Bent et al. (1994), one room in a school was remediated as a pilot test. this process focused on removal of the primary PcB sources, a joint-filling material. the joint-filling material was removed using a freezing process, where the joint-filling material was frozen with liquid nitrogen and then removed together with portions of the masonry. other remediation measures were also performed, including cleaning, stripping of wall paint, and floor cover removal. the average air PcB concentrations in this building was 5,500 ng/m^3. PcB concentrations ranged from 77,700.0 ± 16,339.8 mg/kg (n = 5) for the joint-filling material, 290 mg/kg for the upper Pvc floor covering, and 3,088.0 ± 6.7 mg/kg (n = 3) for the floor adhesive. wipe samples from the walls showed surface contaminations of 7,348.0 ± 1,488.7 µg/m^2 (n = 5) related to contaminated joint-filling material. By stripping off the wall paint in the rooms for a pilot experiment, a reduction in the surface contamination from 3,450.0 ± 410.0 µg/m^2 (n = 2) to 489.0 ± 19.0 µg/m^2 (n = 2) was found. together, the remediation methods lowered indoor air PcB concentrations by 73.8%, with approximately half attributable to the wall paint stripping which decreased levels by 43.6%.

Kontsas et al. (2004) also examined Finnish worker exposures to PCBs during remediation of prefabricated homes. In this study, 24 PCB congeners, including the ten most abundant PCBs in elastic polysulfide sealants, were measured in the serum of 22 exposed and 21 non-exposed men. Corresponding personal air samples were also collected. Total serum PCB concentrations (as assessed using the 24 measured congeners) in the exposed workers ranged between 0.6 and 17.8 micrograms per liter (µg/L). Serum PCB concentrations for ten people exceeded the Finnish upper reference limit for occupationally non-exposed people (3 µg/L). Non-exposed workers had lower serum PCB levels, ranging between 0.3 and 30 µg/L.

3.1.2 Physical removal of Light ballasts

Review of the available literature associated with PCB-containing light ballasts and light fixtures suggests that PCB-containing light ballasts should always be considered when conducting a PCB source identification and remediation project. According to the EPA Region 10 (1993), when a PCB-containing light ballast fails, measures should be taken to limit or avoid personal exposure. Detailed cleanup and decontamination procedures for a leak, including management and disposal of wastes from PCB-containing ballasts, are outlined on EPA's PCB laws and regulations web page (EPA, 2010a-b).

Schools in the United States built before 1979 can potentially have fluorescent light ballasts that contain PCBs. Failed or leaking fluorescent light ballasts may contribute to levels of PCBs in the air and on surfaces inside school buildings. The typical life expectancy of these ballasts is 10-20 years and EPA has seen evidence of leaking PCBs in light ballasts in schools in Oregon, North Dakota, and Massachusetts. The capacitor in the ballast may contain PCBs and typically has 0.1 kg of PCB fluid. Ballasts manufactured in the United States after 1978 are labeled "No PCBs", and therefore any unlabeled ballast from the United States should be assumed to contain PCBs (UNEP, 1999).

Several research projects show the impact of PCB-containing light fixtures on indoor PCB concentrations (NYC DOE, 2010; MacLeod, 1981; Funakawa et al., 2002). During the New York City school project, investigators noticed elevated indoor PCB concentrations in spaces without PCB caulk, and identified PCB-containing ballast in lighting fixtures. After replacement of lighting fixtures, the indoor air PCB concentration in one of the classrooms decreased from 2950 ng/m^3 to 81 ng/m^3. Defective PCB-containing light ballasts have been shown to emit PCBs and to be an important source of indoor PCB contamination (MacLeod, 1981). This research demonstrated a 50-fold increase in airborne PCB concentrations after the burnout of PCB-containing ballast and elevated PCB levels for 3-4 months after the burnout event. A field study in Japan found total PCBs in indoor air of 26 - 110 ng/m^3 for an office with PCB-containing light ballasts (Funakawa et al., 2002). These authors also reported that mixture of PCBs in indoor air of the office was similar to the composition of PCBs emitted from the light ballasts during chamber tests.

There are significant costs associated with PCB-containing light ballast replacement. However, there are also significant costs and risks that may be incurred by not replacing these fixtures. A study prepared for the Department of Energy (SAIC, 1992) evaluated four solutions for addressing PCB-containing light ballasts and concluded that a program that is preventive in nature provides the most economical solution. Removal of PCB-containing light fixtures benefits the indoor environmental quality of a school by reducing potential impact of PCBs. In addition, replacement of old PCB containing light fixtures offers a significant energy savings benefit. According to EPA (2007), proactive replacement of PCB-containing light fixtures can reduce the potential high cost of cleanup and relocation of students that may be associated with a ballast leak or failure. It is important to note that Federal law requires removal and disposal of leaking PCB-containing ballasts and disposal of any PCB-contaminated materials at an EPA-approved facility.

3.2 Source modification

Source modification based on chemical degradation or extraction of PCBs in building materials was discussed in several peer-reviewed journal articles and conferences identified by the literature search. Key characteristics of these methods are presented in Table 3.4 and additional information about these methods is provided in the narrative that follows.

3.2.1 chemical degradation

Tanner (2010) discussed the Amstar dechlorination liquid, a product based on a nucleophilic substitution reaction reported to remove chlorine from PCBs without generating toxic byproducts or waste. This method has been shown to decontaminate steel ship bulkheads successfully and, to a lesser extent, soil, railroad ballast materials, and bulk oil as well. For bulkheads with PCB levels greater than 100 ppm, Amstar was shown to reduce PCB contamination by 90 – 99%. Tanner (2010) reports that Amstar is currently being tested on painted surfaces, coated surfaces, caulks, soils and bulk oils. However, no results from the testing were available in time for this report.

tabLe 3.4 Summary of Source Modification Methods for Abatement of PcB-containing Building Materials

method	description	example	applied buildings materials	references
degradation	An activated metal within a solvent system and thickening agent to form a paste. the technology extracts PcBs from materials such as paints and soils. the extracted PcBs react with the activated metal and are degraded into by-products.	Activated Metal treatment System	Painted surfaces, concrete, caulk and other adhesives, soil	(a), (b), (c)
	Nucleophilic substitution reaction that removes the chlorine from the PcBs without heat.	Amstar dechlorination liquid	concrete, dust, metal surfaces, insulation, paints, gaskets, soil	(d)
chemical extraction	Performance-based organic decontamination solvents.	capsur® (aqueous based), Hexane (solvent-aqueous solution), kerosene, diesel, terpene hydrocarbons, techxtract®, Aluminum Brightner	Porous-material (concrete, granite, brick)	(e), (f), (g), (h), (i)
	Double-wash-rinse procedure described in 40 cFR§ 761 Subpart S. 1) detergent wash, 2) potable water rinse, 3) solvent wash, and 4) solvent rinse.	Z-Green®, Big orange® Industrial Degreaser Solvent, or any solvents in which PcBs are 5% or more soluble	concrete	(h), (i)
cleaning	Removal of residual PcBs from non-porous surfaces including PcBs sorbed to settled dust.	Mineral spirits, HEPA vAc, commercial cleaning agents (e.g. Simple Green, tSP), kerosene, diesel, terpene hydrocarbons, pine soap-water solution, wet cleaning	Non-porous material (e.g., metal and glass), dust	(c), (e), (g), (j), (k), (l)

References

a) Quinn, 2010
b) Novaes-card, 2010
c) Ruiz, 2010
d) tanner, 2010
e) tEI, 2009
f) w&c, 2009
g) Mitchell, 2001
h) Scadden, 2001
i) w&c, 2010a-f
j) EH&E, 2010f
k) Bent, 1994
l) kuusisto, 2001

In conference abstracts, Quinn et al. (2010) and Novaes-Card et al. (2010) discussed plans to present results from laboratory testing of the Bimetallic Treatment System (BTS) and the activated metal treatment system (AMTS), both of which use zero-valent magnesium (ZVM) in an acetic acid/ ethanol solution to remove and rapidly degrade PCBs in structural coating materials, such as paint. Researchers from National Aeronautics and Space Administration (NASA) and University of Central Florida (UCF) previously demonstrated rapid and complete dechlorination of PCBs in PCB-containing aqueous/solvent systems, showing total degradation of up to 50 nanograms per microliter (ng/µL) of PCB-151 in one hour (Novaes-Card et al., 2010). In paint, AMTS was shown to reduce PCB levels in some samples from 2,797 mg/kg to 29 mg/kg in seven days. These methods removed PCBs without destroying the polymeric lattice structure of the paint. The technical report from these researchers (Ruiz et al., 2010) further evaluated the performance of BTS at two Department of Defense (DoD) facilities. The performance criteria were tested for; i) distribution and adherence, ii) adherence of sealants, iii) ease of implementation, iv) reduction of PCB concentration in treated paint to less than 50 mg/kg, v) reduction in PCB concentration in BTS paste to less than 50 mg/kg, and vi) impact to paint adherence. The BTS demonstrated strong performance in adherence and ease of implementation criteria. The PCB concentration of paint and concrete surfaces were reduced to less than 50 mg/kg (starting concentration of approximately 500 mg/kg) in approximately 1 week after application. However, after application of BTS, the adhesive qualities and adherence of the surface layer of paint was negatively impacted. A cost analysis for concrete and metal treatment with BTS concluded that for porous materials, such as concrete coated with PCB-containing paint, treating the concrete and paint with BTS and reusing the building structure is more cost effective than demolishing the building. However, for nonporous structures (i.e., metal tank) coated with PCB-containing paint, disposing the untreated tank to a TSCA landfill and replacing with a new tank is at least $80,000 cheaper than the alternative methods. These cost analysis results are summarized in Table 3.5.

For porous materials, such as concrete coated with PCB-containing paint, the cost analysis shows that it would be most cost effective to treat the concrete, paint with BTS, and reuse the building, as

tabLe 3.5 Remediation cost Analysis of concrete (porous) and Metal(non-porous) Surface coated with PcB-containing Pa

concrete building coated with Pcb containing Paint (250 mg/kg)		
Demolition, untreated and disposed of in a tScA landfill	Demolition, treated prior to demolition with BtS, disposed of in a non-hazardous landfill and recycled	No demolition, structure treated with BtS and reused.
$200,000	$180,000	$150,000
metal tank coated with Pcb containing Paint (250 mg/kg)		
Untreated and disposed of in a tScA landfill	Remove paint using sandblasting, waste sent to tScA landfill and metal tank recycled	treated with BtS and painted metal tank recycled
$25,000	$105,000	$140,000
Source: Ruiz, 2010		

compared to demolishing the building. However for nonporous structures (metal tank) coated with PCB-containing paint, the cost analysis shows that it would be more cost effective to just dispose of the metal structure and replace it with a new one.

Kume et al. (2008) developed a catalytic degradation method of removing PCBs using palladium on an activated carbon-triethylamine (Pd/C-Et^3N) system at ambient hydrogen pressure and temperature. Though this reagent has not been applied to building materials such as caulk and concrete, the reagent was tested in paraffin oil and PCBs from capacitor and completely dechlorinated the PCBs into biphenyls.

Barkley (1990) compared performance and cost analysis between physical removal and chemical degradation of PCBs in concrete. Physical removal was conducted using shot-blasting, which is a technique using steel shot to remove surface layers of contaminated concrete. The chemical dechlorination technique used IT/SEA Marconi reagent, consisting of a polyethylene glycol-based mixture. The warmed (heated) liquid is applied several times using a sprayer, brush or roller, and then the reagent is allowed to remain in place undisturbed for 2-3 weeks. Forty pre- and post-remediation concrete core samples were collected for each remediation method. The pre-remediation concentration ranged from 0.13 – 65 ppm for shot-blasting and 4.6 – 60 ppm for IT/SEA Marconi treatment. The percent reduction of PCB concentration in concrete after the shot-blasting method ranged between 15 – 96% (average 68%) and IT/SEA Marconi treatment ranged between 11 – 97% (average 73%). Cost analysis concluded that the IT/SEA Marconi reagent method ($0.85/sq ft) is more cost-effective than the shot blasting method ($2.19), especially since shot-blasting is labor-intensive and generates contaminated waste that requires disposal at a permitted hazardous waste facility. The commercial availability of IT/SEA Marconi reagent is unknown.

3.2.2 chemical extraction and cleaning

Various means of cleaning PCB-contaminated materials were reported to precede source encapsulation or follow bulk removal. Some of the methods were described in case reports while others were identified in conference proceedings and other grey literature.

A commercial solvent designed for PCB extraction known as CAPSUR® was noted in several case reports and presentations (W&C, 2007; W&C, 2008b; W&C, 2010c; W&C, 2010e; TEI, 2009; Mitchell and Scadden, 2001). Woodward & Curran, Inc. (W&C) conducted several pilot studies to test the effectiveness of a commercial product, CAPSUR®, in removing PCBs from vertical and horizontal concrete surfaces (W&C, 2007; W&C, 2008b; W&C, 2010c; W&C, 2010e). CAPSUR® is an aqueous-based solvent with emulsifiers for the cleanup of PCBs. After removal of caulk, CAPSUR® was applied to each joint using a hard bristle brush for approximately 5 minutes. Then the product was left for 30 minutes, followed by rinsing with clean water and vacuuming off the visible chemical from each surface. After a single application of CAPSUR®, the post treatment PCB concentration increased by 1.2 to 4 times. W&C (2010e) continued to test this product by applying multiple coats (up to 10 coats) of CAPSUR® with multiple rinses. However the post-treatment results were variable and did not always reach the regulatory limit of 10 µg/100 cm^2. Some of the potential issues of CAPSUR®

addressed by these pilot studies were: lower temperature reduces removal efficiency and insufficient rinsing and vacuuming may have contaminated the verification samples. In addition, approximately 660 pounds of waste materials containing PCBs were produced and building occupants complained about the odor of CAPSUR®. A carbon air filter was installed and the exhaust line was moved to the roofline. Figure 3.3 shows the CAPSUR® application on PCB contaminated concrete conducted by W&C (VanSchalkwyk, 2009).

Ljung et al. (2002) evaluated a new approach for extraction of PCBs from concrete based on the concept of a "sacrificing sealant". If efficacious, such a method could limit reliance on labor-intensive and costly methods for bulk removal of contaminated concrete. In the in situ trials reported by Ljung (2002), 90 small sections of contaminated sealant (caulk) were removed from linear sections of sealant, leaving numerous small holes in each section. Each hole was filled with one of three "sacrificing sealants", either a modified silicone-polymer (MS-pol), polyurethane-1 (PU1), or polyurethane-2 (PU2) sealant. The sacrificing sealants were analyzed for PCB concentrations after remaining in the holes for one, two or three months. Results from these tests showed increasing PCB concentrations over time for MS-pol and PU1, but not PU2. Results suggested that the "sacrificing sealants" needed at least two months for the PCBs to migrate into the sealants. However, even after two months, the PCB-content in the "sacrificing sealants" was low, as less than 0.1% of the original sealant PCB concentration was found. The authors concluded that this "sacrificing sealant" method was not effective at extracting PCBs from adjacent materials over the time frames studied.

In presentations by Scadden and Mitchell (2001), cleaning and source encapsulation methods used to remediate PCB-contaminated concrete floors were summarized and their efficacy was examined. Cleaning methods for PCB-contaminated concrete floors included a double-wash-rinse procedure (Title 40 Code of Federal Regulations CFR Section 761.30(p)), which is required to prepare PCB-contaminated concrete for encapsulation. The surface washing steps used for this remediation included a detergent wash (1:3 ratio of water and Z-Green, ZEP Chemical Company), a potable water rinse, a terpene hydrocarbon solvent wash (Big Orange Industrial Degreaser Solvent, ZEP Chemical Company), and a solvent rinse. The detergent washing resulted in a cleaner surface and resulted in generally lower PCB concentrations on the concrete surface, while PCB levels remained the same or slightly higher during the solvent wash and rinse steps. The floors were subsequently scrubbed with a 30% muriatic acid solution

fIGure 3.3 cAPSUR® application on PcB-contaminated concrete surface

(Source: w&c, 2009)

to roughen the concrete surface and ensure epoxy adherence to the surface. After abrasion, the floor was again washed. Two coats of the encapsulant (Armorseal 700 HS, Sherwin Williams Company), hard epoxy coatings, were then applied to the concrete surface, with the coats in contrasting colors. Cracks, bubbles, soft spots, and small pinholes were found immediately after application, likely due to inadequate mixing of the encapsulant. These problems were repaired by grinding the affected areas and replacing with a new epoxy topcoat, with pinholes filled with a Sherman Williams high-strength polymer product and applying additional epoxy. No information on the effectiveness of the epoxy coatings was presented.

Scadden and Mitchell (2001) reported the costs for the double-wash-rinse and encapsulation activities were $23.75 per square foot of floor area. Additional costs for these procedures included $6.85 per square foot for transportation and disposal of wastes, and $39,000 for engineering oversight and analytical costs.

Bent et al. (1994) published two case studies of PCB remediation in German school buildings. In the first case, a twelve-classroom school built in 1971 was remediated. Specific concerns included the interior rooms that were finished with PCB-containing paint and windows that had PCB-containing sealant in the window flashing area. Remediation was performed while the building was in use. Initially, furniture was removed; walls were cleaned with a high-pressure cleaner; lamp shells were removed; ceilings, furniture, and lamp shells were cleaned by damp cloth; drapes and curtains were washed. The upper wax film of the PVC floor covering was removed with 4 – 5 courses of stripping. The PCB joint-filling material was subsequently covered with self-adhesive aluminum foil. Together, these cleaning and encapsulation measures were effective, reducing indoor air PCB concentrations by 68% on average (initial levels= 3,975.0 ± 425.3 ng/m^3, n = 4; remediated levels= 1,267.3 ± 67.7 ng/m^3, n = 7). Elevated outdoor temperature was shown to increase the indoor air PCB levels, pointing to the need for both test and control rooms to assess remediation effectiveness. Similarly, furniture and other classroom materials were also found to be a secondary source of PCBs, as demonstrated by observed reductions in indoor PCB concentrations when they were removed. In contrast, air handling systems (or "air washers") that remove dust from the ambient air using a wet process were shown to have no observable impact on indoor air PCB concentrations.

Pizarro et al. (2002) conducted an experimental study examining the efficacy of cleaning and subsequent encapsulation of PCB-containing concrete. Three cleaning methods and three epoxy-coating systems were tested on PCB-contaminated and non-contaminated concrete core samples. Cleaning methods included hand rubbing of a sulfuric acid-based detergent Aluminum Brightener (Hotsy Equipment Company, Mars, PA), high pressure wash with a sodium hydroxide-based Ripper II (Hotsy Equipment Company, Mars, PA), and a multi-step chemical sequestration system TechXtract (Active Environmental Technologies, Mount Holly, NJ). Both the Aluminum Brightener and Ripper II were diluted 1:5 by volume. Three epoxy-coating methods were also analyzed: (1) Plastite system (Wisconsin Protective Coating, Green Bay, WI), (2) Chemicote system (Garland Floor Company, Cleveland, OH), and (3) Corobond system (Sherwin-Williams, Pittsburgh, PA). Each coating method included a primer and two layers of epoxy coatings. The performance of the cleaning methods was evaluated using wipe tests before and after cleaning, with post cleaning tests conducted every other day for two weeks and every other week for the next eight months. At the end of the eight month period, a two-inch core sample was taken from the PCB-containing cement block. Similarly, the effectiveness of the coating systems were tested on concrete cores, each cleaned with TechXtract prior to coating. Surface wipe samples were collected preand repeatedly post-coating at the same weekly intervals. After the eight month sampling period, pull tests were performed using an elcometer to test coating adhesion strength, with a subsequent core sample taken for sectional analysis of PCBs.

Results for the experiments reported by Pizarro et al. (2002) showed that cleaning methods alone were an ineffective long-term solution for containing PCBs in concrete, as cleaning removed a portion of PCBs from only the first inch of concrete. Bleed-back of oil and PCBs occurred within days after cleaning for all cleaning methods, which was attributed to capillary rise of the oil in which the PCBs were dissolved.

table 3.6 Summary of Engineering controls Used for Mitigation of PcB-containing Building Materials.

method	technique	description	example	applicable building media	references
contact encapsulation	2 stage epoxy	Application of a primer that forms a bond with the PcB-containing material, followed by application of two layers of epoxy coating.	Armorseal 700 HS, Plastite System, chemicote System, Perma-crete, Sikagard 62, Sikaflex-15 LM, Macropoxy 646	Porous material (concrete, granite, brick)	(a), (b), (c), (d), (e)
	Glazing barrier	Application of conventional surface coatings to limit migration of PcBs and minimize potential for dermal contact.	Silicone, acrylic paint	Porous material (concrete, granite, brick)	(a)
	Paint		Latex paint, low voc oil-based paint	Porous material (concrete, granite, brick)	(f),
	Sealant		caulk	Porous material (concrete, granite, brick)	(g), (h), (i)
Physical barrier	wall, fence, isolation	Limit migration of PcBs and minimize potential for dermal contact and transport of PcB vapors.	Interior walls, exterior fences, isolation with polyethylene sheeting, self-adhesive aluminum foil, mini-wall or false wall	Soil, external wall, ceiling, caulk	(f), (g), (h), (i)
Ventilation	Introduce ventilation, modify existing HvAc	Increase the outdoor air ventilation within an interior space to reduce concentrations of PcBs in indoor air and associated inhalation exposure.	Adjust temperature set points, modify HvAc operation schedule, open windows, modify exhaust and/or supply flow, increase air flow with axial flow	Indoor air	(g), (h), (i), (j)
air cleaning	Filtration	Remove PcB vapors from indoor air by absorption onto organic carbon rich sorption media	commercial air cleaners with high capacity activated carbon filters or equivalent	Indoor air	(i)

References
a) tEI, 2009
b) Mitchell, 2001
c) Scadden, 2001
d) tRc Engineers, 2010b-c
e) w&c, 2010a-f
f) tRc Environmental, 2010
g) EH&E, 2010f
h) Bent, 1994
i) EH&E, 2010a-e
j) EH&E, 2007a-b

Bleed-back was greatest when low-pH cleaning reagents were used or when hydraulic oil was added to the PCB-contaminated concrete after cleaning. For TechXtract, the efficiency of PCB removal was enhanced when the concrete surface was heated, as heating accelerated the bleedback process and thus lowered surface PCB concentrations. The authors concluded that surface heating (together with a system to capture volatilized contaminants) is a potentially viable remediation approach.

3.3 ENGINEERING CONTROLS

Engineering controls for mitigation of PCB-containing materials were discussed in several reports identified by the literature search. These controls include contact encapsulation, physical barriers, ventilation, and air cleaning. Key characteristics of these methods are provided in Table 3.6 and additional information about these methods is provided the narrative that follows.

3.3.1 Contact Encapsulation

Contact encapsulation refers to application of a barrier directly on top of PCB-containing materials. The objective of contact encapsulation is to block contact with PCBs in those materials and to impede volatilization of PCB vapors. Documents identified by the literature search that focused on source encapsulation included 1 peer-reviewed journal paper and 6 technical reports. These papers examined several encapsulating methods, some of which included cleaning prior to encapsulation.

Important properties to consider when choosing a coating include elongation (i.e., its elasticity or rigidity), dry film thickness, hardness, drying or curing time, and compatibility with existing surfaces (W&C, 2010f). Epoxy-type coatings are widely used for PCB encapsulation. Epoxy coatings generally consist of a three-part epoxy-polyamide coating applied in a primer layer, clad leveler, and surface layer. Encapsulants applied to floors should include two coatings of contrasting color to indicate when resurfacing is required due to wear (Mitchell and Scadden, 2001).

Specific products such as Sikagard 62 have been approved by EPA Region 1 to encapsulate exposed surface of the brick, extending out a minimum of 4 inches from the caulk joint (EH&E, 2007a-b). Once the sealant has dried and a visual inspection has been conducted and the necessary confirmatory sampling has been conducted (approximately 72 hours after application), a caulking material, Sikaflex, was applied to weatherize the building. A few groups conducted power washing of the concrete walls prior to applying the encapsulant to ensure proper contact between the concrete (ATC, 2010; W&C, 2010f). The scrubbing head on the hand-held pressure washer was designed with a vacuum to collect the wash water. Rubber membrane troughs were placed below wash locations to collect wash water not collected by the scrubbing head vacuum and ran down the building. The collected wash water was pumped to holding tanks.

A two-part system comprised of bond breaker tape and silicone caulk has been used to encapsulate PCB-containing caulk as an interim mitigation measure. The bond breaker tape provides a PCB barrier, and the silicone caulk provides a top coat that further limits opportunities for direct contact with skin. Post-remediation wipe sampling of the silicone caulk sealant has shown this system to be effective for at least 5 months (EH&E, 2011a).

TABLE 3.7 Summary of Implementability, Effectiveness, and Aesthetics of Various Encapsulants							
	Sikagard 62 Epoxy (Gray)	EnviroSeal 20 (Clear)	Sikagard 670W (Clear)	Sikagard 670W (Gray)	Sikagard 550W Elasto-color (Gray)	Sikaflex 2C (Bronze)	Sil-Span (Bronze)
Application Properties	Highly viscous, short pot-life; able to be sprayed or painted on; effectively coats surfaces to desired extent. Rating: Fair	Very liquid upon application (runs like water), drips beneath masked edges on masonry; full-scale use would only be practical if applied to entire panels. Rating: Poor	Relatively easy to apply, does not run on vertical surfaces with thin and even coats; effectively coats surfaces to desired extent. Rating: Good	Very easy to apply (consistency of a typical exterior latex paint), does not run on vertical surfaces with thin and even coats; effectively coats surfaces to desired extent. Rating: Good	Very easy to apply (consistency of a typical exterior latex paint), does not run on vertical surfaces with thin and even coats; effectively coats surfaces to desired extent. Rating: Good	Two-part caulking; installation is typical of exterior caulking. Rating: Good	A preformed silicone profile strip is affixed to the surface of the concrete panel with an adhesive applied on either side of the caulked joint. Rating: Good
Effectiveness	Effectively contained concrete with residual PCBs > 200 ppm at 5 to 7 locations inside joint, and concrete with concentrations > 100 ppm at 3 to 4 locations within 0.5" of joint; maximum reported with result of 1.1 ug/100 cm^2 inside joint and 3.9 ug/100 cm^2 within 0.5" of the joint. Rating: Good	Somewhat effective in containing residual PCBs > 100 ppm within 0.5" of the joint – one wipe sample reported at 0.9 ug/100 cm^2. Somewhat effective in containing residual PCBs < 25 ppm at 0.5-3" from the joint – two wipe samples reported at non-detect and one reported at 35 ug/100 cm^2. Rating: Fair	Effective in containing residual PCBs > 100 ppm within 0.5" of the joint and residual PCBs < 25 ppm at 0.5-3" from the joint – two wipe samples from each interval reported at non-detect (4 sample total). Rating: Good	Effective in containing residual PCBs < 25 ppm at 0.5-3" from the joint – one wipe sample reported at non-detect. Rating: Good	Effective in containing residual PCBs > 100 ppm within 0.5" of the joint – one wipe sample reported at non-detect. Somewhat effective in containing residual PCBs < 25 ppm at 0.5-3" from the joint – one wipe sample reported at 0.6 ug/100 cm^2. Rating: good	PCBs reported ND at 5 out of 6 sample locations (6th location reported at 0.6 ug/100 cm^2) – 17 out of 18 wipe samples reported at non-detect using a hexane-preserved, a saline-preserved, and a dry wipe at each location. Rating: Good	Effective in containing residual PCBs within the joint and the adjacent concrete face covered by the Sil-Span – three wipe samples reported at non-detect using a hexane-preserved, a saline-preserved, and a dry wipe. Rating: Good
Aesthetics	Cured project creates a nonporous surface coating that is initially very glossy, but appears streaky and discolored after long-term exposure to sunlight (non UV-resistant); however, epoxy in joint would be beneath caulking. Rating: Fair	Cured product appears invisible – matches the appearance of adjacent uncoated concrete. Rating: Good	Cured project has a glossy / shiny appearance, slightly distinguishable from adjacent uncoated concrete at edge of coated area. Rating: Good	Cured product dries evenly and in a color true to the chart used for color selection; surface has a matte appearance and a natural feel and finish similar to the underlying concrete. Rating: Fair	Cured product dries evenly and in a color a shade lighter than the chart used for color selection; surface has a matte appearance and natural feel and finish similar to the underlying concrete. Rating: Fair	Typical of exterior caulking; can be color matched to the current caulking color or to the adjacent building surfaces. Rating: Good	The strip covers a width of approximately 2 inches over the ¾-inch wide caulking joint; multiple colors available. Rating: Fair

Continued

TABLE 3.7 Continued

	Sikagard 62 Epoxy (Gray)	EnviroSeal 20 (Clear)	Sikagard 670W Clear	Sikagard 670W Gray	Sikagard 550W Elastocolor (Gray)	Sikaflex 2C (Bronza)	Sil-Span (Bronze)
Summary & Recommendations	Although the implementation and aesthetics received fair ratings, this product is most effective at encapsulating high level residual PCBs and is recommended (or a similar epoxy-type product, e.g., Sikadur 35) for use in the joints after caulking removal.	Given the poor implementability and fair effectiveness, this product is not recommended for use in full-scale implementation.	Given its good ratings in each category, this product is recommended for use on concrete surfaces adjacent to caulk joints; full-scale application would result in minimal changes to the appearance of the façade.	Although this product is easily implementable and effective, the colored finish may not be a desirable option from an aesthetic standpoint.	Although this product is easily implementable and effective, the colored finish may not be a desirable option from an aesthetic standpoint.	Easily implementable, effective, and color options are available to achieve desired outcome. Implementation would result in minimal changes to the appearance of the façade.	Although this product is fairly easy to implement and is effective, the two-inch wide colored strip over the joint may not be a desirable option from an aesthetic standpoint.

Source: W&C, 2010f

Application Property Notes: Good ratings were given to any product that was easy to apply in comparison to typical exterior paints or caulking materials. Fair ratings were given to any product where application or use of the product was more complicated in comparison to easier products. Poor ratings were give to any product that is not recommended for full-scale implementation.

Effectiveness Notes: Good ratings were given for products where surface wipe samples collected after application were reported as non-detect or close to non-detect for PCBs. Fair ratings were given for products where surface wipe samples collected after application were reported at higher levels for PCBs, but achieved at least some level of contaminant reduction. No products were given poor ratings.

Aesthetic Notes: Good ratings were given to any product that does not markedly change the appearance of the façade. Fair ratings were given to any product where the final appearance of the façade would be visibly distinct from the present appearance. No products were given poor ratings.

According to results of a study by Pizarro et al. (2002), coatings were an effective containment solution for PCBs in concrete (as assessed for an eight month testing period), provided that the concrete surface was aggressively cleaned to maximize oil extraction and minimize bleedback and was patched to provide a smooth surface prior to primer application. Aggressive cleaning is difficult to achieve on vertical surfaces for cleaning methods that rely on extended residence time for cleaning agents on the concrete. High-pressure washing over sufficient duration may be effective on vertical surfaces. Coatings were not effective when free oils were present on the concrete surface prior to coating or if the concrete was heated.

In all cases, long-term monitoring plans need to be put in place to ensure the integrity of the seal. W&C (2010f) conducted a pilot study to test seven encapsulant products based on implementability, effectiveness, and aesthetics. With overall evaluations, they concluded the most successful product was Sikagard 62 epoxy in the joint (in direct contact with caulk) and Sikagard 670W clear on adjacent concrete. The summary table was reproduced from that report and is presented in Table 3.7.

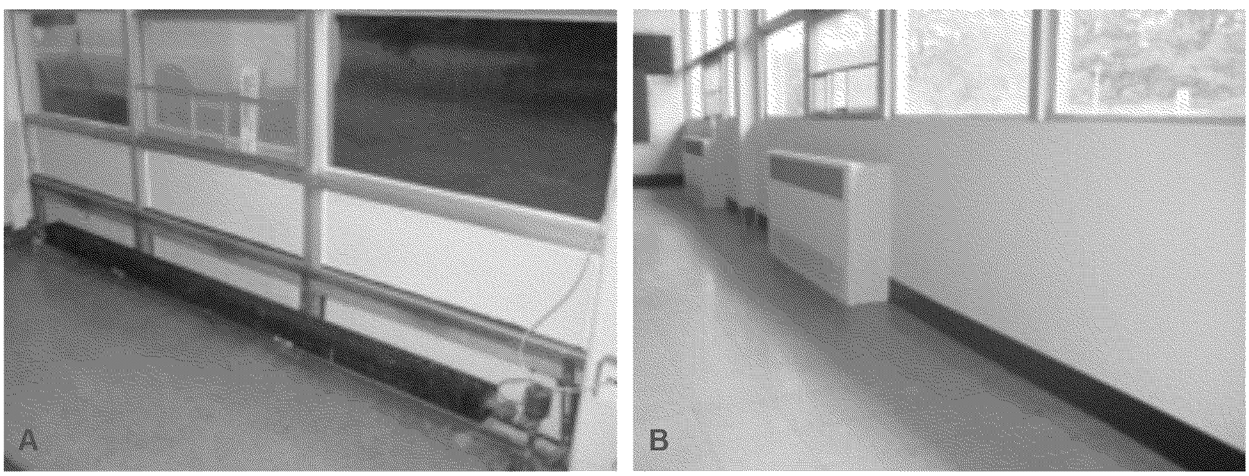
3.3.2 Physical Barriers

Physical barriers can be used to separate areas with PCB-containing building materials from other areas of a building. The fundamental objective in most cases is to minimize opportunities for direct contact with materials that contain PCBs or to mitigate emissions of PCB vapors to air. The type and configuration of physical barriers will depend on the disposition of PCB-containing materials and how the building is used.

Fences and interior walls prevent building occupants from coming into direct contact with PCB-containing building materials. A simple plastic mesh snow fence was placed around the perimeter of a building façade to prevent people from approaching or contacting PCB-containing caulk on the exterior face of a school (EH&E, 2010f). As noted in Section 3.1.1, a "false wall" was constructed over walls covered by PCB-containing paint in order to prevent direct contact with the PCBs on the original painted surface (TRC Environmental, 2010).

An example of a false wall or "mini-wall" is depicted in Figure 3.4. At the time this building was constructed, PCB caulk was used to seal the joint between the aluminum framing and composite

FIGURE 3.4 Panel A – Photograph of Pre-installment of Mini-walls/Panel B – Photograph of Post-installment of Mini-walls



(Source: EH&E, 2010b)

panels shown in Panel A of the figure. Mini-walls were constructed over the framing to prevent opportunities for contact with the caulk and to impede transport of PCB vapors to indoor air (Panel B of the figure). The mini-walls were constructed first by installing foil coated foam board insulation over each section of composite panel and sealing the joint between the aluminum frames and insulated foam board (EHE, 2010b). The foam board and framing was then covered with wall board, sealed, and painted to match classroom walls. New cove base was added to complete the mini-wall construction.

Physical barriers have also been used as an interim measure to minimize contact with soil contaminated by building-related PCBs. In this application, geofabric and fresh mulch have been placed over the contaminated soil, and clean materials such as stone were used to cover the ground surfaces (W&C, 2010d).

In addition to blocking contact, physical barriers can be used to minimize emissions or transport of PCB vapors within a building. Barriers to control vapor transport include sealants or foam applied to joints of building features that form interstitial spaces which include PCB-containing materials. Examples of interstitial spaces that may enclose PCB-containing materials include aluminum framing around the panels of a curtain wall sealed with PCB caulk or wallboard covers over structural beams that are sealed with PCB caulk. Filling void space at select points in an interstitial space or sealing the joints of materials that form the interstitial space will block transport pathways for PCB vapors and lower the potential for subsequent inhalation exposure. In one school, spray foam insulation was injected into aluminum framing adjacent to PCB caulk, and the metal-to-metal joints of an I-beam cover were sealed with Sikaflex 2C to minimize PCB migration pathways (EH&E, 2010c). A limitation of this approach is that the sealants have the potential to absorb PCBs over time and could eventually qualify as PCB Remediation Waste. Monitoring interim measures such as these should be part of an operations and maintenance plan as discussed in Section 3.4.2.

Physical barriers can also be useful for addressing a limitation of encapsulation methods. Depending on the color of the building materials and sealant, encapsulation can be conspicuous on the exterior face of a building. Owners and occupants of some buildings have expressed concerns over the aesthetics of encapsulated areas. For example, a physical barrier was used as a substitute for a layer of encapsulant in one building. After PCB-contaminated caulk was removed from metal window joints, one or two layers of epoxy encapsulation were applied to the adjacent brick. Next, metal panels (also called metal flashing) were constructed as an extension of the existing metal window frame and installed over the brick surfaces to achieve the required two layers of encapsulation. The flashing was painted to match the color scheme of the building (W&C, 2010f).

3.3.3 Ventilation

Ventilation is a means of controlling concentrations of PCBs in indoor air independent of source removal or source modification. Ventilation is not useful for addressing requirements for PCB waste under 40 CFR§761, but it has been shown to be effective for modifying indoor air concentrations and lowering exposures to building-related PCBs.

Bent et al. (2000) included intensive ventilation to reduce indoor air levels. In this approach, PCB-remediated rooms were ventilated at air exchange rates greater than 5 air exchanges per hour for three weeks following the removal of all primary and secondary sources of contamination. Ventilation plus other remediation procedures led to reductions of PCB concentrations in indoor air to below 600 ng/m^3 from the initial concentration of 6,000 – 7,000 ng/m^3.

Ventilation was also shown to be important in a pilot study conducted in three New York City school buildings (NYC DOE, 2010). In this study pre- and post-remediation air tests were performed with windows closed. Pre-remediation tests showed elevated PCB concentrations in all three schools, with mean levels in the classrooms of two schools ranging between 842 and 1,609 ng/m^3. After removing exterior PCB-containing caulk from the schools, post-remediation PCB levels in the same schools were generally lower, as mean PCB concentrations in the classrooms ranged between 450 and 807 ng/m^3 However, all areas remained above the targets for PCBs in indoor air of schools suggested by EPA (see Table 1.3). Following removal of PCB-containing light ballast and additional ventilation, mean PCB concentrations in the classrooms decreased substantially (142 – 450 ng/m^3), with most areas under the EPA guidance criteria. Similar impacts of source removal and ventilation were found for the schools' common spaces (gyms, halls, stairways, etc.).

A school remediation project in Massachusetts also showed that ventilation can be an effective method for reducing PCB concentrations in indoor air (EH&E, 2010a-f). Indoor air PCB levels were attributable in part to emissions from caulk along the interior seams of composite panels that formed portions of curtain walls along the building envelope. Increased outdoor air flow through unit ventilators and central exhaust systems decreased concentrations by 2 to 4 times for classrooms throughout the school. Similar results were reported for another educational building in Massachusetts (EH&E, 2007b).

Increased ventilation has the potential to distribute PCB-containing dust from duct work or other surfaces in a building. However, comprehensive and regular cleaning of surfaces is effective at limiting accumulation and transport of PCB-laden dust.

3.3.4 air cleaning

The literature search identified one report which suggests that operation of air cleaners equipped with activated charcoal can be effective at controlling concentrations of PCBs in indoor air.

Two portable air cleaners, each operating at a flow rate of 400 cubic feet per minute (cfm) were operated in two closed classrooms for 24 hours (EH&E, 2010c). Assuming complete mixing of air in the rooms, the air cleaners provided a recirculation rate of approximately 5.8 air exchange per hour (h^{-1}). The PCB concentrations in indoor air of the rooms measured during the final 8 hours of air cleaner operation were 80 ng/m^3 and 111 ng/m^3. Indoor air PCB levels measured before the air cleaner experiment were 209 ng/m^3 and 364 ng/m^3, respectively. Outdoor air ventilation rates to the rooms were approximately 2 h^{-1} during both the baseline and air cleaner monitoring periods. These results indicate approximately a 3-fold reduction in concentrations of PCBs in indoor air attributable to operation of the air cleaners. The change in concentration was in direct proportion to the recirculation rate of the air cleaners assuming complete mixing of air within the rooms.

Noise generated by air cleaners and the potential for 'short-circuiting' and incomplete mixing of indoor air is a limitation to their use in sensitive occupied environments such as classrooms. More information on efficacy of air cleaners in relation to noise and mixing is needed to evaluate air cleaning as an effective means of mitigating impacts of PCB-containing building materials.

3.4 Administrative Controls

Property owners and managers have an important role in managing and mitigating impacts of PCB-containing materials in buildings. Property owners and managers make decisions about priorities for remediation; identify, fund, and implement mitigation plans and programs; and establish and implement operations and maintenance plans. The administrative controls available to property owners and managers to help fulfill their role are discussed in this section.

3.4.1 Space assignment

Considerations for establishing priorities for mitigation efforts have been outlined by EPA (EPA, 2010c) and include the following;

1. PCB concentration and conditions – building materials with the highest PCB concentration, materials located in locations with direct sunlight, and caulk that is not intact (e.g. peeling, brittle, cracking) have a high potential for release of PCBs,
2. Accessibility – building materials contaminated with PCBs that are easily accessible to building occupants have the potential for direct contact (dermal or ingestion) or indirectly through the air handling system,
3. Occupancy – areas with higher occupancy should receive a higher priority. Consideration should be given to relocating occupants possibly affected by mitigation efforts.

The presence of potentially vulnerable populations should also be considered when establishing the schedule of the PCB mitigation project. For instance and as shown in Table 1.2, EPA suggests that targets for PCBs in indoor air of schools should be age dependent and generally inversely related to age (EPA, 2009c; EH&E, 2011b). The literature contains at least one example of a case in which an administrative approach to risk management explicitly considered the information on differential background exposure among age groups. In that case, kindergarten students were re-assigned from rooms in the original and PCB-containing portion of a school to a newer and non- PCB-containing section of the building (LPS, 2010).

3.4.2 Work Plans

As noted earlier, work plans and operations and maintenance (O&M) plans are important parts of a management system for remediation of PCB-containing building materials. Work and O&M plans offer a multitude of opportunities for administrative controls intended to mitigate impacts of building-related PCBs on occupants and operations of a building.

The 40 CFR§761 regulations for PCBs require that a work plan be prepared prior to commencing any PCB remediation actions at a building. The self-implementing procedures for removal or cleanup of PCB-contaminated building materials require notification and submission of a work plan at least 30 days prior to the cleanup of site under 40 CFR§761.61. The plan must include a description of the abatement and mitigation activities, proposed cleanup levels, removal and abatement procedures, verification sampling procedures, waste storage and handling procedures, and disposal options.

Five EPA-approved PCB remediation plans were identified (ATC, 2010; W&C, 2010a-f; W&C, 2008a-c; W&C, 2007; EH&E, 2007b). Overall the remediation plans contain similar components that are tailored to each building and project setting. The following sections summarize the common remediation plan elements.

Case Narrative

All of the EPA-approved remediation plans identified by the literature search contain a case narrative or background information section. The case narrative includes a description of the building, the location of PCB-containing building materials, and an overview of abatement goals of the remediation project. The narrative also typically contains a description of how the PCB-containing materials were initially identified and plans for follow-up assessments designed to characterize the extent of PCB-containing materials in each building. Photographs, building plans, and site maps are included in the narrative to provide a complete description of the project and its surroundings.

Regulations, Permits, and Qualifications

Federal, state, and local regulations vary slightly from project to project and require close coordination with EPA, state and local agencies. The identification of the applicable regulations and corresponding approval required to perform each building-related PCB remediation project is critical to a successful project. Elements of 40 CFR§761 that are critical to most work plans are:

§761.20: PCB Concentration Assumptions for Use
§761.61(a): Self-implementing on-site cleanup and disposal of PCB remediation waste
§761.61(c): Risk-based disposal approval
§761.62: Disposal of PCB Bulk Product Waste
§761.79(c) Self-implementing decontamination procedures
§761.79(h) Alternative decontamination or sampling approval

Project Scope

The project scope section of a work plan provides an overview of the project application, operation, and goals to evaluate effectiveness. The project scope will also include the identification of materials to be abated and a summary of mitigation methods. In addition, the specific PCB-containing materials and remediation waste streams associated with each material will be described in this section.

Project scope may be broken down into work phases based on an overall renovation schedule or building layout. A description of what will be required in each phase and the associated PCB remediation waste generated by the abatement phase will also be described in this section of the remediation plan. The description of the abatement work normally consists of the following general elements: site isolation and protection, source containment and removal, material disposal, decontamination and/or removal of PCB residues, acceptance testing and verification and site restoration.

Assumptions and expectations of the abatement contractor that are needed to carry out the scope of work are usually presented in the project scope section of the plan as well. Finally, criteria for acceptance of the remediation work is presented and predicated on obtaining successful testing and inspection results along with completing the site restoration activities.

Execution Plan

The execution plan provides a description of work flow ranging from site preparations to work sequence. Key components of site preparation include ground cover and site isolation. Ground cover is necessary in order to prevent debris from escaping the work zone and to protect existing facilities and the environment. Remediation plans typically detail that the abatement contractor shall use sufficient ground cover along areas where work will take place. Conventional water-impervious membrane coverings secured into the ground in each respective work area are standard. The covering is specified to extend sufficiently from the outside edge of the building or work area to capture any loose remediation debris.

Some projects indicate that on top of the secured membrane a single layer of 6-mil polyethylene sheeting be temporarily secured. This sheeting is designed to collect dust and debris from removal and disposal without impacting the secured membrane in contact with the ground. Remediation plans state that it is important for the abatement contractor to remove and control abatement debris by HEPA vacuuming continuously throughout the work shift and again at the end of each work shift.

Site isolation is required during all phases of PCB abatement work. The remediation plan addresses the security and access concerns as part of each project. Under certain conditions wind barriers in conjunction with local exhaust controls (e.g., HEPA vacuums) are required to minimize airborne dust generated during the project.

The general work sequence for the various remediation tasks is presented in each remediation plan. The general work flow is described in the following steps: site protection, source removal, surface cleaning, material decontamination, waste disposal, testing and verification, site restoration, project acceptance and completion.

Remediation Procedures

PCB remediation plans provide a detailed description of procedures for source removal, source modification and, if planned, engineering and administrative controls. Descriptions of remediation methods identified by the literature search are provided in Section 2 and earlier portions of Section 3 in this report.

Storage and Disposal

Plans for storage and disposal of PCB waste are necessary components of PCB remediation plans. PCB Bulk Product Waste (e.g., caulking), once removed, is specified to be stored for disposal in accordance with 40 CFR§761.40 and §761.65. The work plans identified by the literature search indicate that storage typically consists of placement into a secure and lined container or into an appropriate temporary container (e.g., 6-mil plastic disposal bag) followed by transport into a PCB container at the end of a work shift. Once in the container, these materials must be covered and protected from the weather.

All containers and temporary containers must be clearly marked as PCB-containing waste materials as required under §761.45. Lined and covered barrels containing PCB materials must be marked with designations indicating that the PCB materials are contained in the barrel, as stated in 40 CFR §761.65(c)(1). In addition, secondary containment such as a tarp can be used to prevent spillage onto the floor of the storage area. When not in use, containers should remain covered by both lids and tarps. All areas containing PCB waste must be secured.

Rags and/or cleaning materials, polyethylene sheeting, and PPE used to clean PCB-contaminated materials shall also be disposed as PCB remediation waste or disposed of in accordance with 40 CFR§761.61(A)(5)(v).

When a container is full or the remediation work is complete the PCB remediation waste is placed under manifest and transported to a TSCA waste disposal facility. Management of manifests, shipping records, and certificates of disposal are part of the storage and disposal recordkeeping process.

Abatement Completion Acceptance Criteria

Identification of performance criteria and evaluation procedures for the mitigation actions are always included in PCB remediation work plans so that final approval of the remedial work can be given when the acceptance criteria conditions have been met. Examples of completion acceptance criteria include:

- Visual inspections to confirm that all surfaces are free of dust or debris including work areas and that no visible PCB material identified for removal remains in place.
- Surface and bulk sampling to confirm the effectiveness of the remediation activities.
- Successful restoration of the work site to its original or an acceptable condition.
- Completed and accurate waste manifest to document that every PCB waste container removed from the site has been disposed of properly.

Specific completion acceptance criteria are available from selected remediation work plans and include the following examples:

- Porous surfaces in low occupancy area: bulk sample acceptance criterion will be less than or equal to 25 ppm for total PCBs.
- Porous surfaces in high occupancy area: the bulk sample acceptance criterion will be less than or equal to one ppm for total PCBs.

- Nonporous surfaces in high occupancy area: the wipe sample acceptance criterion will be less than or equal to 10 μg/100 cm^2 for total PCBs.
- Nonporous surfaces in low occupancy area: the wipe sample acceptance criterion will be less than or equal to 100 μg/100 cm^2 for total PCBs.
- Encapsulated area: the wipe sample acceptance criterion will be less than or equal to 1 μg/100 cm^2 for total PCBs.

Health and Safety

Health and safety plans developed as part of PCB remediation projects are designed to ensure the health and safety of abatement contractors, visitors to the site, and occupants of the building.

The abatement contractor typically submits a written health and safety plan that details engineering controls, practices and procedures, protective equipment, and training that will be used to control and minimize potential exposures and work related hazards. In addition, the plan will typically include provisions for all relevant health and safety issues. Health and Safety plans include copies of training materials and training records for those who will be working on-site at any time during the abatement project.

All applicable federal and state OSHA standards and regulations to ensure worker safety must be in effect during the PCB abatement process. The following programs should be addressed in the contractor's health and safety plan: Respiratory Protection, Fall Protection, Personal Protective Equipment, Lockout/Tagout, Confined Spaces, Machine Safety, Ladder/Scaffolding Safety, Electrical Safety, Housekeeping (slips, trips, falls), Injury Reporting, First Aid, and Fire Safety. This is not a comprehensive list of the required programs, and the contractor is responsible for determining which programs apply and how best to implement the required programs.

All PCB abatement work plans emphasize public safety around work areas and that the abatement contractor needs to ensure public safety during all phases of the abatement work. Work plans incorporate containment measures designed to protect workers, occupants, and the environment from the release of PCB-containing materials. Containment may include, but not limited to, draping work areas, the use of HEPA filters to collect fugitive emissions during cutting operations, isolation of work areas from occupied areas, blocking off HVAC intakes, and using protective wind screens and fences.

Access to PCB remediation work areas needs to be limited to ensure that only workers aware of the abatement project will be within the work zone. Proper hygiene and decontamination procedures must be followed to limit the potential for transferring PCB remediation waste outside the work area.

During the abatement work, work plans specify visual or quantitative assessment criteria to verify the effectiveness of the containment controls of the abatement contractor. If observations indicate that additional containment or engineering controls are required, the abatement contractor will be responsible for making the necessary adjustments to the engineering controls.

Operations and Maintenance Plan

Continued management of building materials that contain residual amounts of PCBs is sometimes required following the completion of a remediation program. An Operations and Maintenance (O&M) Plan for PCBs is an effective administrative tool for managing any such materials. The details of an O&M Plan are specific to the conditions of a site however the O&M plans reviewed as part of the literature search have similar objectives and requirements.

The objectives of a typical O&M Plan for PCBs are to:

- Anticipate, recognize, control, and mitigate potential PCB hazards at the site.
- Ensure the continued health and safety of building occupants and the community.
- Maintain compliance with federal and local regulations pertaining to PCBs.

Activities undertaken to achieve those objectives generally include:

- Implement proactive maintenance activity reviews to identify work with the potential to disturb PCB-containing materials.
- Maintain air and surface concentrations of PCBs below established targets.
- Specify schedules, plans and follow-up assessments.
- Evaluate all projects or work activities that may potentially disturb PCBs to determine if precautions are required (e.g., inspection, testing, abatement).
- PCB remediation and hazardous materials training will be provide to selected building management employees.
- Allow only qualified and trained personnel to perform activities that will potentially disturb PCB-containing materials.
- Ensure that elements of the O&M Plan are observed.
- Provide PCB awareness training to building occupants.
- Institute a system for all contractors and vendors to report any condition or activity that could result in the disturbance of PCBs to building management.
- Institute a system for reporting all accidental disturbances and/or releases of PCBs to building management for evaluation and follow up.

EH&E undertook a comprehensive review of published papers, reports, and other information to catalog and evaluate remediation methods for PCBs in building materials. This report contains a description of existing methods for abatement of PCB-containing building materials and mitigation of impacts from PCBs in buildings. Information on the strengths and limitations, efficacy, cost, and byproducts of each method is presented, where available.

A multi-step, iterative process was used to ensure that all literature relevant to the scope of work was identified. The literature search identified a total of 92 documents, including peer-reviewed papers, conference proceedings, government and industry reports.

4.1 PCBs in Building Materials

PCBs are a class of compounds that had important commercial uses prior to their ban in 1976 due to their association with adverse human and ecological impacts. Primarily used as a dielectric fluid in capacitors, transformers, and other electrical equipment, PCBs were also used as a component of some non-liquid construction materials and building products manufactured, including: caulking, other sealants, adhesives, paints, floor finishes, light ballasts of fluorescent lights and other items. Concentrations of PCBs in construction materials of many buildings have been reported to exceed levels authorized under the applicable federal regulations (40 CFR§761). Buildings constructed between the 1950s through late 1970s are at risk of having PCB-containing materials. Understanding available mitigation strategies for PCB-containing buildings is a critical issue for governmental, industry and commercial entities.

PCBs can be introduced into building materials in multiple ways. Some building materials, including sealants, paint, and light ballasts, were manufactured to contain PCBs and can be considered primary sources. Construction materials not intentionally manufactured with PCBs can accumulate PCBs released from primary source materials over time. Lastly, PCBs released from building materials are sometimes found in human exposure media such as indoor air, settled dust, and soil. The disposition of these PCB-containing materials, occupational hazards, waste byproducts, and cost are important considerations when evaluating and selecting a remediation method.

A list of building materials reported to contain PCBs in buildings is provided in Table 2.3. Direct human exposure media that have been reported to be impacted by PCBs released from building materials are also noted in the table. Caulk, applied primarily to exterior joints, was the most frequently reported material to be a primary source of PCBs. Caulk also had the highest reported concentration of PCBs with levels commonly in the range of 1,000 to 100,000 ppm and ranging up to approximately 750,000 ppm (ATC, 2010). The most commonly reported mixtures of PCBs in caulk were Aroclor 1254 and Aroclor 1248 (EH&E, 2010f; ATC, 2010; W&C, 2007). Paint and adhesives such as floor tile mastic were also frequently reported to be primary sources of PCBs (Bent et al., 1994; TRC Environmental, 2010). Porous materials such as concrete and brick were frequently reported as secondary sources of PCBs.

4.2 remediation methodS

The literature search identified a wide range of methods for managing PCBs in building materials. Although diverse in purpose and approach, the methods can be grouped according to terminology suggested by EPA for environmental clean-up activities. In this context, *remediation* is an overarching term that encompasses removing PCBs from buildings or limiting the migration of PCBs from sources in buildings. *Abatement* refers to reducing the amount of PCBs in building materials. *Mitigation* is a complement to abatement and refers to controlling exposure to PCBs released from building materials without removing PCBs from a building. A conceptual framework for organizing the remediation methods is illustrated in Figure 2.1. The components of abatement and mitigation shown in the diagram are discussed in the following sections.

4.2.1 abatement methods

The objective of abatement is to reduce the mass of PCBs or PCB-containing materials in a building. Abatement consists of (i) source removal - removing primary and secondary source materials from a building and (ii) source modification - lowering the amount of PCBs in building materials through chemical degradation or extraction techniques. The performance of these approaches to abatement is summarized in Table 4.2 in terms of efficacy, cost, practicality, and potential hazards. These attributes of performance were rated on a relative scale (good, fair, poor) based on the information gathered from the literature review and EH&E's experience in managing remediation programs for PCB-containing building materials.

Source removal methods include physical removal and on-site decontamination of PCB-containing materials. Physical removal involves displacement of bulk material that contains PCBs followed by disposal according to applicable state and federal regulations. In the case of PCB caulking, hand tools such as utility knife, putty knife, scraper, ripping chisel, and bush hammer are typically used to pry beads of caulk from the seams in manageable lengths. Various types of abrasive blasting techniques are physical removal methods that have been applied to surface coatings that contain elevated concentrations of PCBs. In both cases, the removed caulk or surface coating is placed in sealed containers which are stored in a covered roll-off and subsequently disposed of as hazardous waste.

In addition to physical removal of PCB-containing materials, source removal can also be achieved through on-site decontamination. Several products and techniques for chemical degradation of PCBs in bulk product waste and remediation waste materials are described in the literature. In general, the products are applied to PCB-containing materials as a slurry or paste, covered by an overlying material, and left in place for days to weeks as required by the kinetics of the degradation reactions. Spent product and degradation products are waste byproducts of the process.

As shown in Table 4.2, source removal and decontamination methods have been demonstrated to be effective in general at attaining compliance with regulatory requirements. Although efficacious in many situations, source removal and modification procedures can be disruptive, expensive, and impractical in buildings that are occupied or are scheduled for demolition in the near future.

Methods commonly used to remove or modify PCB-containing materials can involve construction practices that generate noise, dust, gases, and require involved containment procedures similar to those used for asbestos. Destructive procedures for removing concrete, brick, mortar, and other substrates that have absorbed PCBs from source material such as caulk are often the most disruptive. Abatement activities can be highly disruptive for populated buildings, especially when swing space is not available. As a result, abatement is often undertaken most efficiently in unoccupied areas of a building or when a building is vacated such as during vacation periods for schools. In addition to being disruptive, destructive abatement methods and relocation of building occupants can be expensive as well. Disruption and cost associated with abatement of PCB-containing building materials can favor mitigation over abatement. Remediation approaches that control PCBs in building materials can therefore help organizations maintain continuity and control costs. In those circumstances, management of impacts arising from PCBs in building materials rather than abatement of the PCB-containing materials may be preferred.

4.2.2 mitigation methods

Mitigation refers to controlling impacts of building material-related PCBs without actually removing PCBs from source materials. The purpose of mitigation is to limit release of PCBs from building materials or their transfer to the environment and locations where people may be exposed. Engineering controls and administrative are two general approaches to mitigation of PCBs in building materials. These approaches consist of actions that block pathways of PCB transport, control concentrations of PCBs in exposure media, or establish building operations that minimize exposure to building-related PCBs.

Mitigation methods can provide interim measures of PCB control and can also be a component of activity undertaken following an abatement action or as part of a management in place program for residual PCBs in building materials. Interim measures are typically planned and implemented to provide an equivalent level of protection to permanent measures and to include activities that do not pose an unreasonable risk of injury to human health and the environment.

Engineering and administrative controls implemented alone or in combination can be effective at mitigating releases of PCBs to the environment and limiting exposure. The relative strengths and weaknesses of the common mitigation methods are summarized in Table 4.2. Engineering controls involve changes to the physical conditions of a building that reduce the magnitude of potential uncontrolled releases of PCBs and corresponding exposure. These controls can take many forms but are principally contact encapsulation; physical barriers; ventilation; and air cleaning.

Contact encapsulation refers to covering PCB-containing materials with an impermeable film or sealant. The sealant serves to reduce potential for dermal contact with PCBs and to retard release of PCB-containing materials or PCBs through weathering, mechanical degradation, or volatilization. Contact encapsulation is described in the literature as a mitigation method for PCB-containing caulk, paint, adhesive, and other materials. Numerous encapsulant products are described in the literature and include certain types of tape, sealants, and epoxies.

TABLE 4.2 Summary of Abatement and Mitigation Methods

Type of Remediation	Approach	Method	Cost and Time	Waste	Performance (Regulatory Guidance)	Practicality	Environmental and Health Risks
ABATEMENT	Source Removal	Physical Removal	Fair – though the disposal cost is estimated at $500 per ton (based on Region 1 data), the manual labor to remove the caulk can be costly, $100/linear ft or $10-20 per square foot.	Poor – stress on landfills is a significant concern, competition for space with other hazardous waste.	Good – meets regulatory standards.	Fair/Poor – very disruptive to building occupancy.	Fair – only if proper controls are in place, improper removal can increase burden of PCBs in surrounding environment and within buildings, increased exposure to remediation workers.
	Source Modification	Chemical Extraction	Fair/Poor – depending on how many applications are required, and depth of contamination.	Poor – large amount of chemical containing PCBs, waste may be flammable.	Fair/Poor – mixed results from W&C reports. In most cases, require encapsulation as post treatment. Testing is required to evaluate efficacy, requires a 761.61(c) or 761.79(h) approval.	Good – other hazard, such as flammability and toxicity of extraction solvent may preclude use in certain situations.	Fair – Potential hazards associated with extraction chemicals, need to be managed.
		Chemical Degradation	Fair – cost analysis reported for paint. The cost seems to depend on what the structural materials are; porous or non-porous material. Reaction times vares and are weather dependent, resulting in significant variability for time to complete.	Good – potentially large waste but with little PCB contamination.	Good - but has only been used in limited locations (superfund sites). In some cases, only been tested for waste materials (prior to disposal). Testing is required to evaluate efficacy, requires a 761.61(c) and/or 761.79(h) approval.	Good – however, only been tested in limited locations.	Good – does not release any toxic chemicals with the exception of some loss of solvent (ethanol), less exposure to remediation workers.
MITIGATION	Engineering Controls	Encapsulation	Good – can be significantly less expensive and faster to implement than source removal. In case of power wash, the cost will increase significantly.	Good/Poor – Minimal waste. In some cases, power wash of the surface is required prior to encapsulation, which leads to large amount of waste, potentially contaminated.	Fair - good for interim measure only, not recognized or authorized control option in regulations, need long-term monitoring. The product/brand should be chosen carefully, based on performance and aesthetic.	Fair/Poor - for aesthetic reasons but good for practicality. May be impractical for non-owner occupied facilities as a deed restriction would likely be required.	Good – only if proper maintenance and management plan are in place.
		Physical Barrier	Good – can be invasive.	NA	Fair – good for interim measure, not a recognized or authorized control strategy in regulations.	Good – similar to implementing ordinary construction techniques.	Good – for interim measures.
		Ventilation	Good/Fair – depends on the capacity and efficiency of installed systems, generally not an option in naturally ventilated buildings.	NA	Fair - good for interim measure, not a recognized or authorized control strategy in regulations.	Good – provide installed systems with sufficient capacity, may increase energy costs.	Good – for interim measures, may increase energy costs.
		Cleaning	Good – can be significantly less expensive and faster to implement than source removal.	Good/Fair - Minimal waste, activated charcoals in the air cleaners need to be replaced periodically.	Fair – good for interim measure, not a recognized or authorized control strategy in regulations. The product/brand should be chosen carefully, based on performance and noise level.	Good – however, only been tested in limited locations.	Good – only if proper maintenance and management plan are in place.
	Administration Control	Space Assignment	Good – typically used in combination with other remediation methods.	NA	Fair -good for interim measure only, not recognized or authorized control option in regulations.	Good – provide existing “swing” space.	Good – only if proper maintenance and management plan are in place.

Physical barriers constructed to separate areas with PCB-containing building materials from other areas of a building is another type of engineering control. In some cases, physical barriers such as fences and interior walls can be erected to prevent building occupants from coming into direct contact with PCB-containing building materials. In other cases, physical barriers can be used to minimize transport of PCB vapors from source materials to occupied areas of a building. Barriers to control vapor transport include sealants or foam applied to joints of building features that form interstitial spaces which include PCB-containing materials.

Ventilation with outdoor air and cleaning of indoor air are engineering controls that can be used to modify concentrations of PCBs in indoor air that are associated with volatilization from PCB-containing materials. Improvements or upgrades to existing ventilation systems have been shown to be effective at lowering concentrations of PCBs in indoor air. However, the cost of heating and cooling outdoor air can be a practical constraint on implementation of this mitigation method. Operation of air cleaners equipped with activated charcoal filters was described as effective at lowering PCB levels in indoor air in one report identified by the literature search.

Mitigation through administrative controls involve changes to the use or maintenance of a building that reduce the magnitude of potential occupant exposures to PCBs or the likelihood of uncontrolled releases of PCBs from source materials. A space assignment plan that places building occupants in locations that yield exposures below established targets for indoor air or other media is an example of an administrative control. Another type of administrative control is work plans for remediation programs which serve to ensure consistent and effective management of a remediation action for PCB-containing building materials. Similarly, implementation of an operations and maintenance plan for residual PCBs in building materials can be effective at evaluating the continued performance of other remediation methods. The performance measures of administrative controls can be informed by a site-specific assessment of PCB exposure and risk.

The selection of remediation methods should be determined on a case by case basis. Nonetheless, most reports indicate that the greatest control of PCBs in building materials is obtained when multiple remediation methods are employed. For example, source removal, encapsulation, and physical barriers in combination with improved ventilation have been successful at managing building-related PCBs in relation to both regulatory requirements and risk-based criteria. The costs of mitigating PCB-containing building materials can be substantial, a fact which underscores the importance of understanding site-specific conditions, establishing practical remediation goals, and selecting the most appropriate remediation methods. The cost for abatement and disposal of PCB-containing caulk and residual PCBs on adjacent surfaces has been reported to range from $9 to $18 per square foot of built space. For 200,000 to 300,000 square foot buildings, costs of mitigation have been approximately $1 million to $3 million. It is important to note that remediation cost varies significantly by type of building and with location (Dalvit, 2011; Strychaz, 2010; USACE, 2000). The majority of the abatement and disposal cost in those situations is related to removal of residual PCBs on building materials adjacent to PCB-containing caulk. Alternatives to source removal for residual PCBs, such as a multi-component mitigation program, are expected to be less costly. The literature search identified several cases where mitigation was effective at controlling release of PCBs and subsequent human exposure.

4.3 recommendatIonS

This research was designed to be a review of available literature regarding mitigation methods. During the course of this research EH&E identified several opportunities for additional data gathering and analysis that could further the aims of U.S. EPA related to management of PCBs in building materials. EH&E makes the following recommendations for additional research:

- Expand the scope of this review to include information sources outside of the published literature such as EPA Regional PCB Coordinators and owners of large portfolios of property known or expected to be impacted by PCBs. This second group would include federal organizations such as the General Services Administration, NASA, U.S. Armed Forces and U.S. Postal Service, as well as State property management agencies. Non-governmental groups may include universities and commercial property owners.

- Conduct controlled and independent efficacy demonstrations and trials for a variety of chemical degradation and extraction procedures, as well as encapsulation methods. Performance over time and relevance to real-world conditions should be a focus of these trials.

- Characterize the long-term performance of mitigation methods, such as encapsulation. This can be accomplished by surveying contractors with active and closed remediation projects and collecting samples in those buildings over time.

- Develop guidance for establishing strategies to manage PCB-containing building materials and which detail procedures for:
  - characterizing the presence and condition of those materials,
  - assessing potential exposure to building-related PCBs,
  - selecting appropriate remediation methods, and
  - designing an operations and maintenance program.

- Conduct a cost-benefit analysis of abatement versus mitigation for PCB Bulk Product Waste (primary source materials) and PCB Remediation Waste (secondary source materials) to support policy decisions on management of PCB-containing materials. Consider:
  - amount (mass) of PCBs in primary and secondary source materials in buildings,
  - disruption of building operations associated with abatement and mitigation,
  - magnitude of human exposure to PCBs associated with primary and secondary source materials, and
  - efficacy , cost, and residual risk of abatement and mitigation methods.

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tabLe a.1 Electronic Indices of Scientific and technical Publications Queried		
name	Publisher	description/reason for Inclusion
MEDLINE®	National Library of Medicine	Identify studies published in peer-reviewed scholarly journals with focus on clinical medicine in the United States. MEDLINE is searchable on the web via PubMed.
Infotrieve®	Infotrieve, Inc.	Identify studies published in pre-reviewed scholarly journals, conference proceed ings and government documents. A global full-service information management company – including contents of almost 150 of the leading scientific, technical, and medical publishers.
ScienceDirect®	Elsevier	Identify studies published in peer-reviewed scholarly journals not covered in MEDLINE. coverage is more international than MEDLINE.
Pascal	wolters kluwer Health/ ovID	capture European literature not otherwise included medically oriented databases – basic science, environmental health, chemistry, and biology.
web of Science	thomson Reuters	International coverage of the scientific and biomedical literature, including over 10,000 journals worldwide and over 110,000 conference proceedings.
BIoSIS Previews®	thomson Reuters	Identify original research reports and reviews in biological and biomedical areas, as well as content summaries, books, and meeting abstracts. this is the world's most comprehensive reference database for life science research.
Enviroline®	Dialog	International coverage of periodicals particularly focused on the environment.
British Library	British Library	Access to British Library catalogue, including millions of books and journals online. Also, "Inside conferences" – complete coverage of conference literature.
NtIS	National technical Information Service	covers primarily U.S. federal government-sponsored technical reports from agencies including the EPA, DoE, and HUD, with some coverage of state and local documents. Also includes technical reports from certain agencies in other countries including Japan, the Uk, Germany and France.
oStI	DoE office of Scientific and technical Informa- tion	International scientific and technical research literature.
EPA Publications office	US Environmental Protection Agency	Primarily covers US environmental regulations, proposed rulings, government-sponsored technical reports, etc.
ERIc	Educational Resources Information center	Database with access to more than 1.3 million bibliographic records of journal articles, books, research syntheses, conference papers, technical reports, and policy papers.
Ec Research and Ec Joint Research centre	European commission	captures Ec literature, including latest advances in research, with access to Europa and coRDIS databases.
UN Documenta- tion: Research Guide	United Nations	United Nations documentation, including reports, resolutions and meeting records. International scientific and technical research literature focusing on various envi ronmental and human health issues.
wHo	world Health organization	Indentify wHo documents and research access to wHoLIS (wHo Library and Informa tion Networks for knowledge) database.